NATIONAL ENERGY TECHNOLOGY LABORATORY

Overview of DOE's Gasification Program

Jenny B. Tennant

Technology Manager - Gasification

U.S. DEPARTMENT OF ENERGY

Presentation Outline

- History & Gasification Chemistry
- Gasification-Based Energy Conversion Systems
- Commercial Status
- Environmental Benefits
- DOE Program Overview
- Gasification Cost & Performance Study

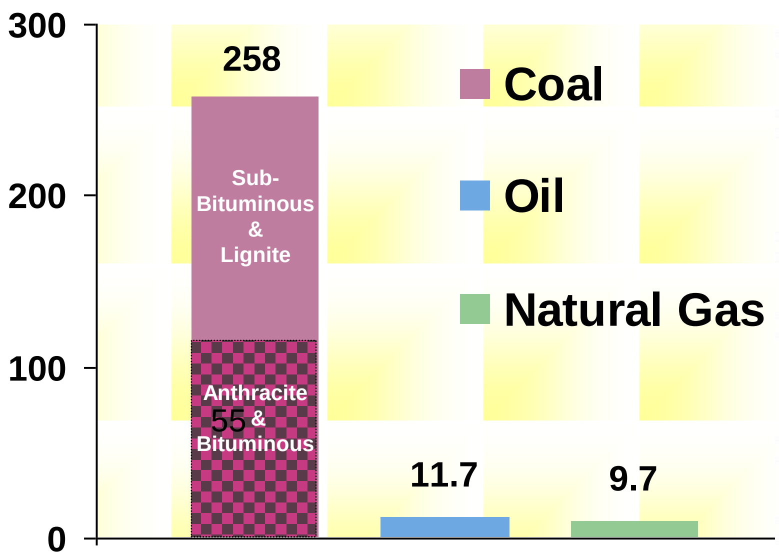
"Coal is an abundant resource in the world ... It is imperative that we figure out a way to use coal as cleanly as possible."
Dr. Steven Chu, Secretary of Energy

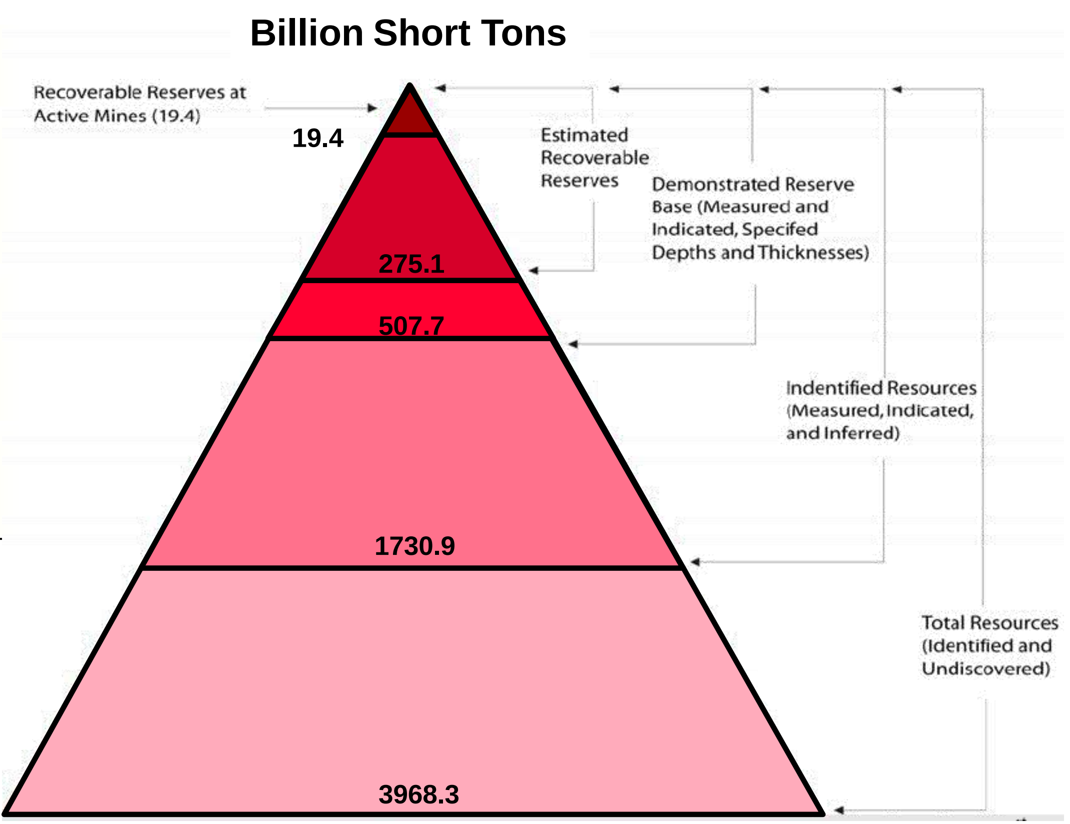
Why the Interest in Gasification?

- **Continuing high price of fuels**
  - Natural gas & highway transportation fuels
- **Energy security**
- **Gasification is baseline technology for H_2, SNG, fuels from coal, and capture of CO_2 for sequestration**
- **Excellent environmental performance of IGCCs for power generation**
- **Growing environmental community view of IGCCs as best technology option for coal systems**
- **Uncertainty of carbon management requirements and potential suitability of IGCC for CO_2 controls**
- **Potential for performance guarantees**

U.S. has a 250 Year Supply of Coal at Current Demand Levels!

U.S. Fossil Fuel Reserves / Production Ratio



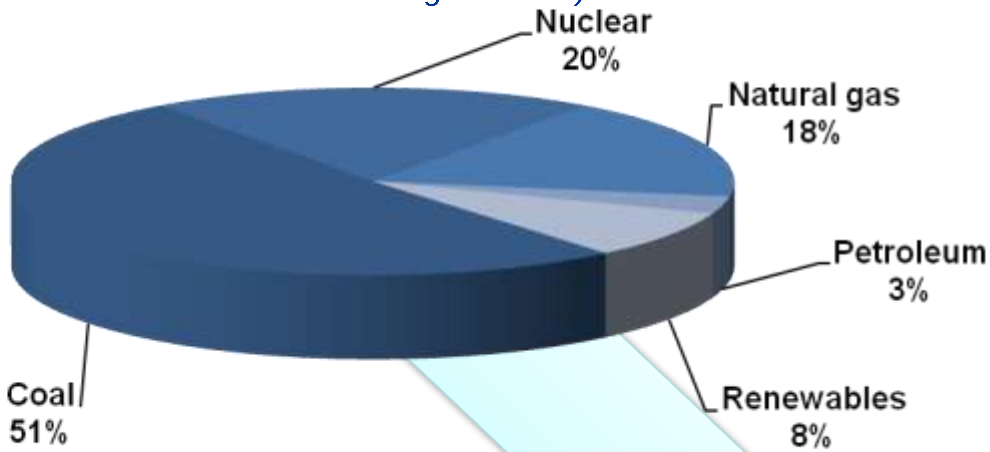


Sources: BP Statistical Review, June 2004, - for coal reserves data – World Energy Council; EIA, Advance Summary U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 22, 2004 - for oil and gas reserves data
Pyramid figure: NRC – "COAL: Research and Development to Support National Energy Policy", Summer 2007

U.S. Electricity Generation by Fuel Type

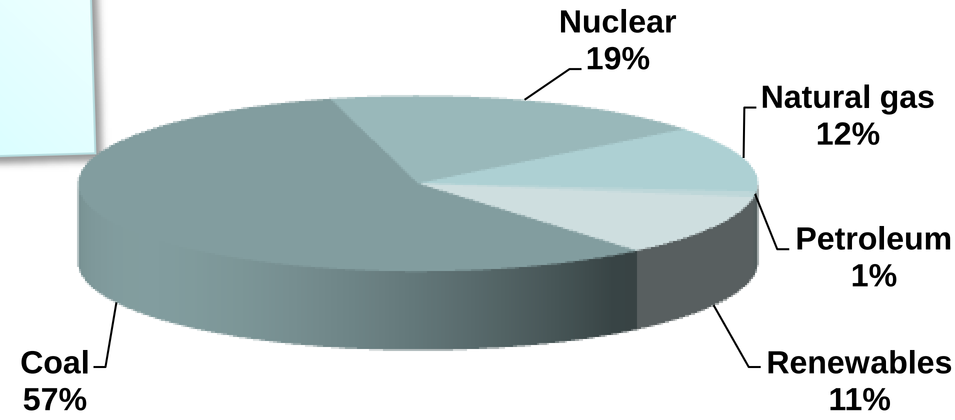
Base Case 2005

(~91% Thermoelectric – steam generation)



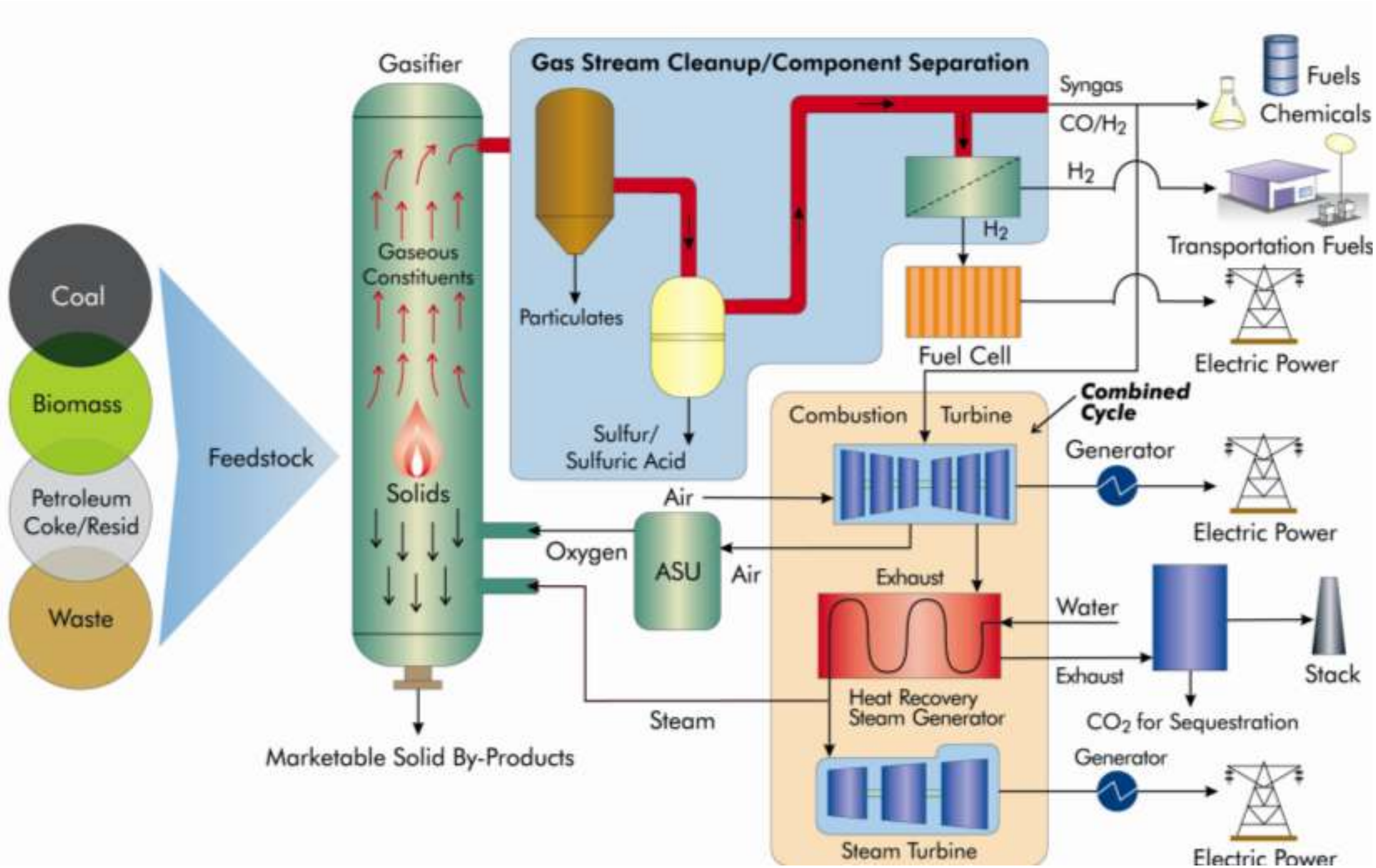
Reference Case 2030

(~86% Thermoelectric – steam generation)



Reference: Energy Information Administration / Annual Energy Outlook 2008

Overview of Energy Systems Options



What is Gasification?

Gasification converts any carbon-containing material into synthesis gas, composed primarily of carbon monoxide and hydrogen (referred to as syngas)

Syngas can be used as a fuel to generate electricity or steam, as a basic chemical building block for a large number of uses in the petrochemical and refining industries, and for the production of hydrogen.

Gasification adds value to low- or negative-value feedstocks by converting them to marketable fuels and products.

Benefits of Gasification

- **Feedstock flexibility**
  - A very wide range of coals, petcoke, liquids, wastes, biomass can be utilized
- **Product flexibility**
  - Syngas can be converted to high valued products: electricity, steam, hydrogen, liquid transportation fuels, SNG, chemicals

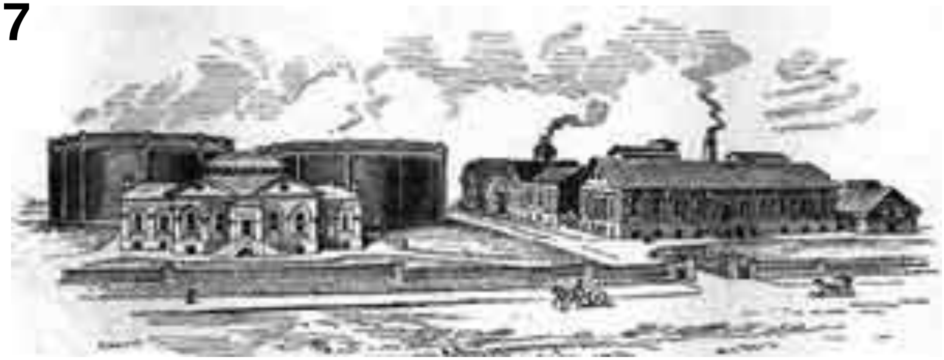
- **Environmental superiority**
  - Pollutants can be economically controlled to extremely low levels (SO_2, NOx, CO, Hg, etc.)
  - Reduced water consumption
  - Potential solid wastes can be utilized or easily managed
  - High efficiency / low CO_2 production
  - CO_2 can be easily captured for sale or geologic storage (sequestration)

History of Gasification
Town Gas

Town gas, a gaseous product manufactured from coal, supplies lighting and heating for America and Europe.

Town gas is approximately 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide.

- **First practical use of town gas in modern times was for street lighting**
- **The first public street lighting with gas took place in Pall Mall, London on January 28, 1807**
- **Baltimore, Maryland began the first commercial gas lighting of residences, streets, and businesses in 1816**



History of Gasification

- Used during World War II to convert coal into transportation fuels (Fischer – Tropsch)
- Used extensively in the last 50+ years to convert coal and heavy oil into hydrogen – for the production of ammonia/urea fertilizer
- Chemical industry (1960's)
- Refinery industry (1980's)
- Global power & CTL industries (Today)

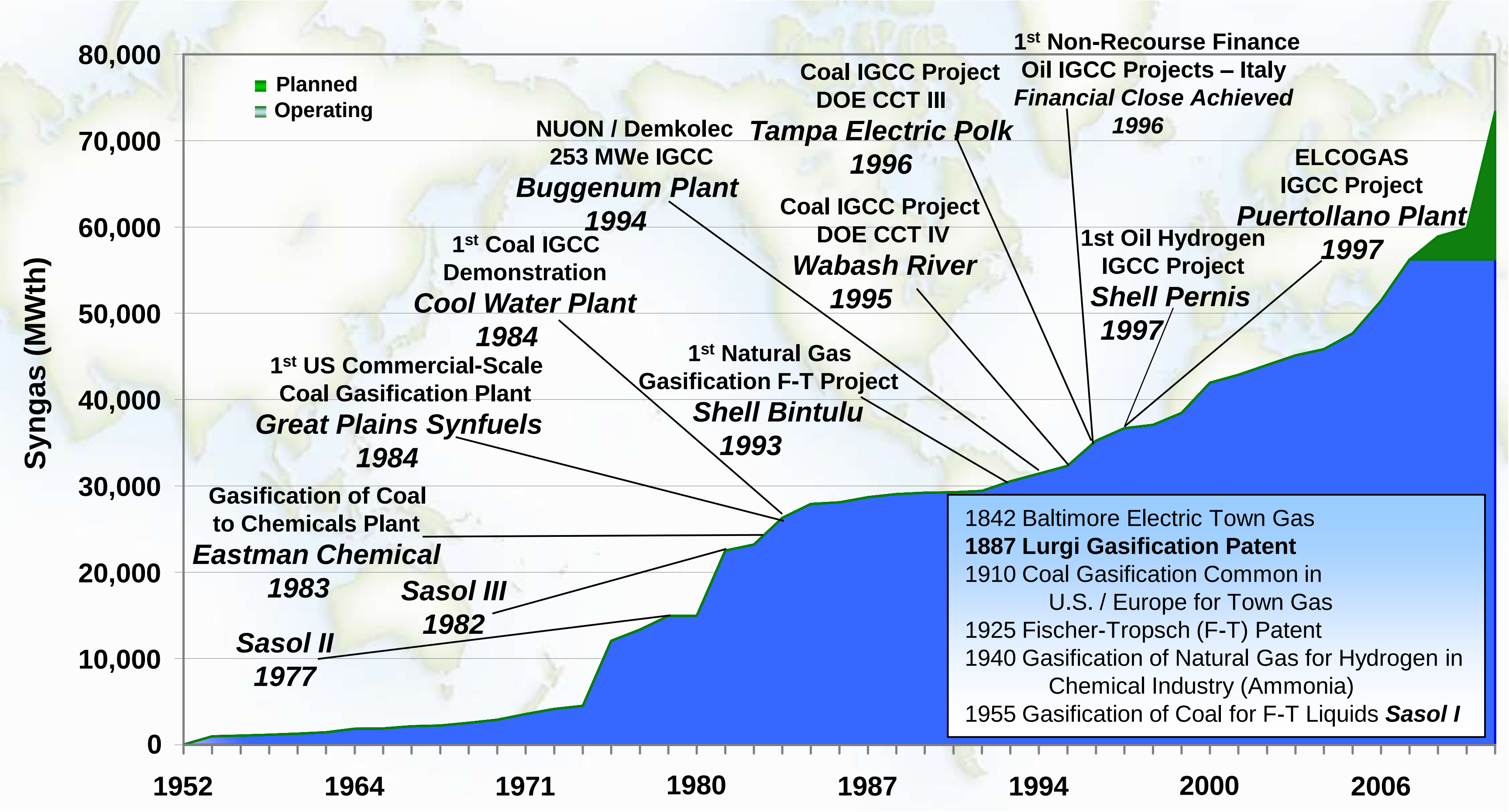
Major Gasification Milestones

1842	Baltimore Electric Town Gas
1887	**Lurgi Gasification Patent**
1910	Coal Gasification Common in U.S. / Europe for Town Gas
1940	Gasification of Natural Gas for Hydrogen in Chemical Industry (Ammonia)
1950	Gasification of Coal for Fischer-Tropsch (F-T) Liquids (Sasol-Sasolburg)
1960	Coal Tested as Fuel for Gas Turbines (Direct Firing)
1970's	IGCC Studies by U.S. DOE
1970	Gasification of Oil for Hydrogen in the Refining Industry
1983	Gasification of Coal to Chemicals Plant (Eastman Chemical)
1984	**First Coal IGCC Demonstration (Cool Water Plant)**
1990's	First Non-Recourse Project Financed Oil IGCC Projects (Italy)
1993	First Natural Gas Gasification F-T Project (Shell Bintulu)
1994	NUON/Demkolec's 253 MWe Buggenum Plant Begins Operation
1995	PSI Wabash, Indiana Coal IGCC Begins Operation (DOE CCT IV)
1996	Tampa Electric Polk Coal IGCC Begins Operation (DOE CCT III)
1997	First Oil Hydrogen/IGCC Plant Begin Operations (Shell Pernis)
1998	ELCOGAS 283 MWe Puertollano Plant (Spain)
2007	Clean Coal Power R&D 250 MWe IGCC Plant Begins Operation (Japan)

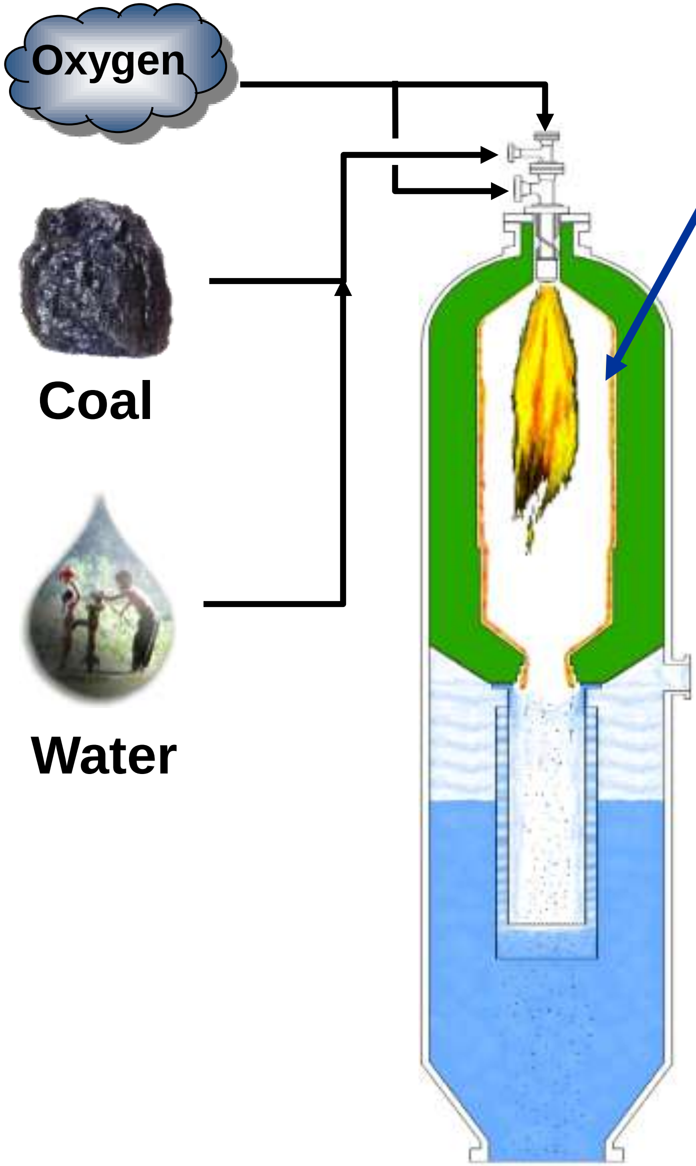
Today IGCC is an Accepted Refinery and Coal Plant Option

Worldwide Gasification Capacity and Planned Growth

Cumulative by Year



What is Coal Gasification?



Extreme Conditions:

- 1,000 psig or more
- 2,600 °F
- Corrosive slag and H_2S gas

Products (syngas)

CO (Carbon Monoxide)
H_2 (Hydrogen)
[CO/H_2 ratio can be adjusted]

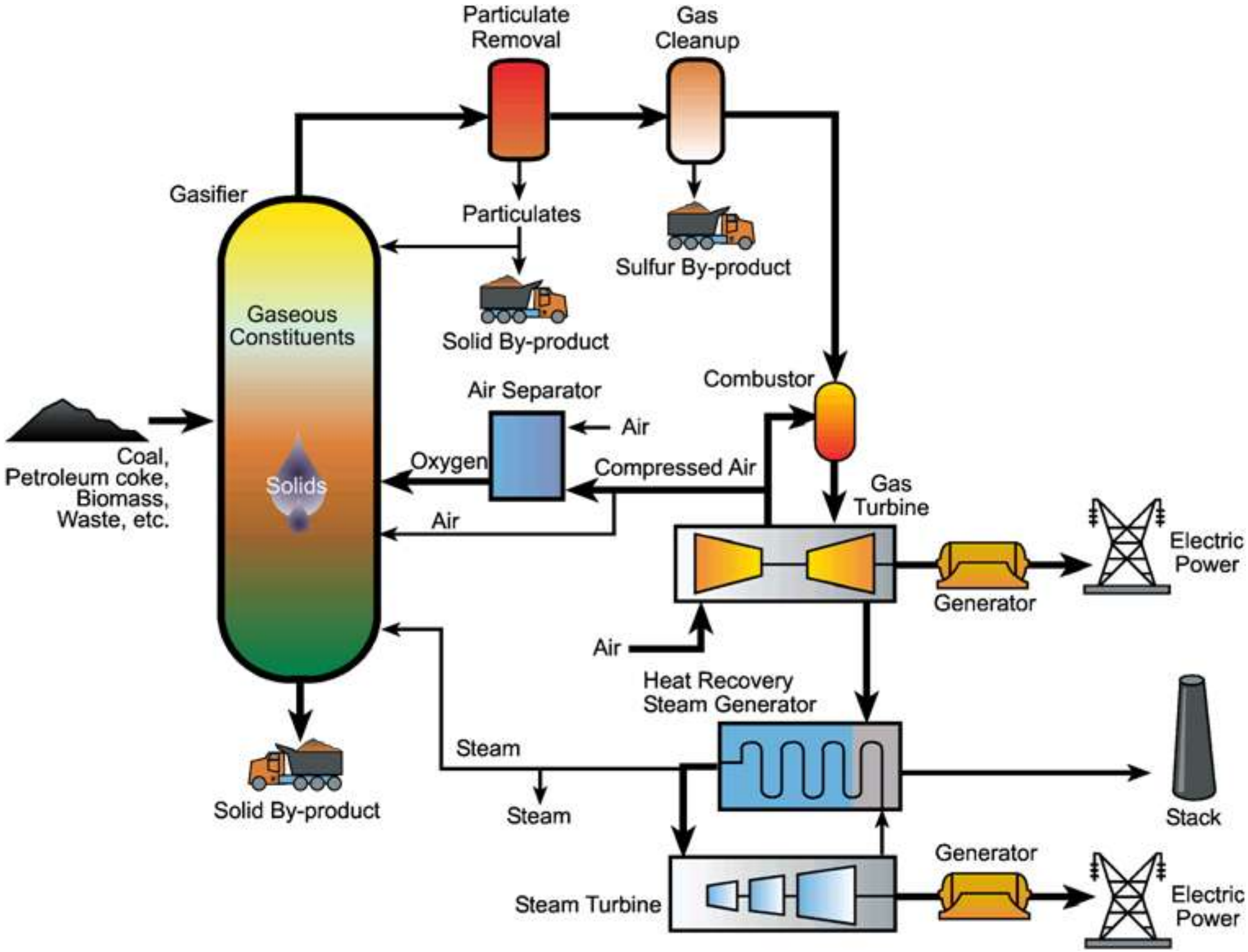
By-products

H_2S (Hydrogen Sulfide)
CO_2 (Carbon Dioxide)
Slag (Minerals from Coal)

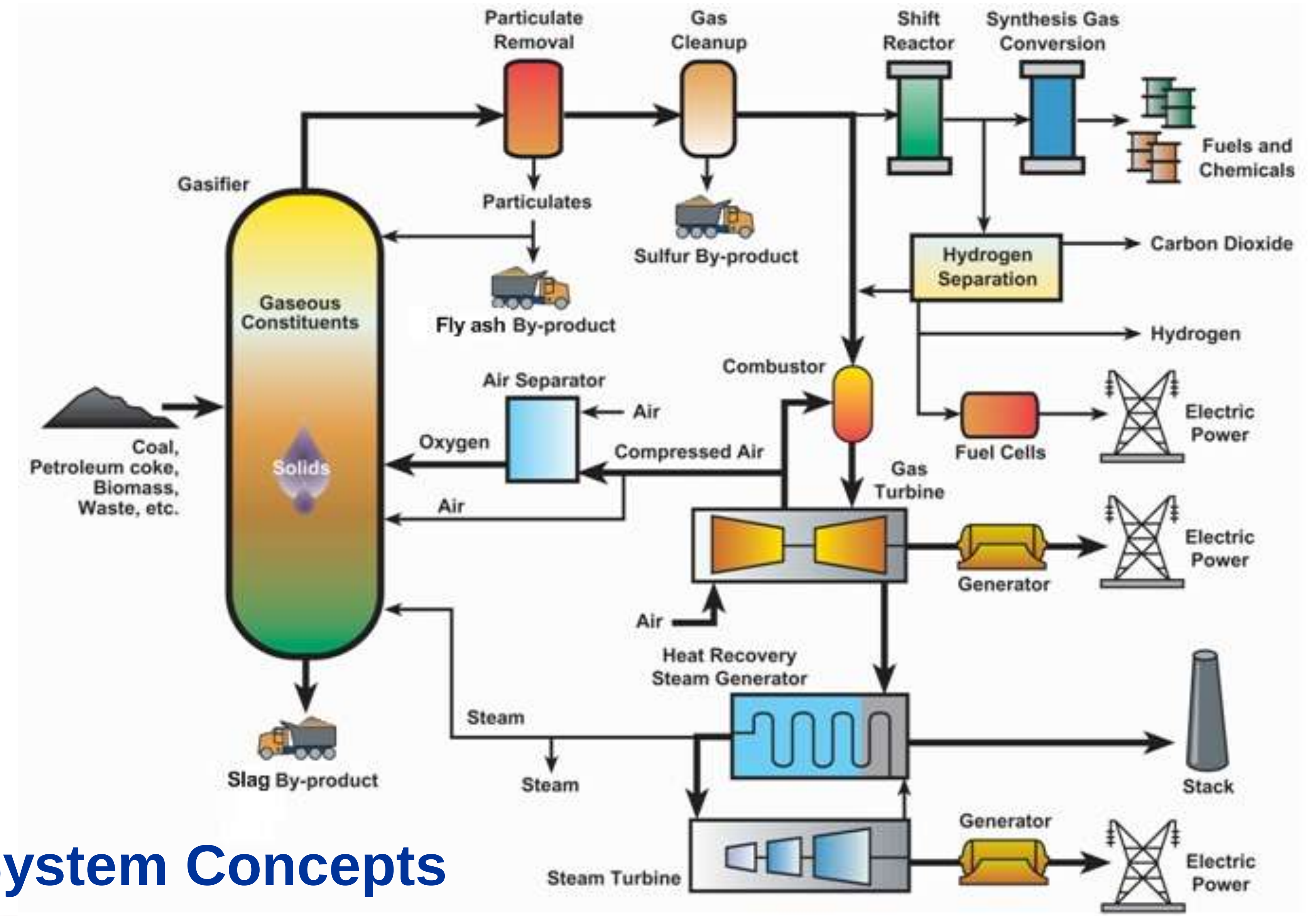
Gas Clean-Up *Before* Product Use

Courtesy: Eastman Chemical

Gasification-Based Energy Production



Gasification-Based Energy Production



System Concepts

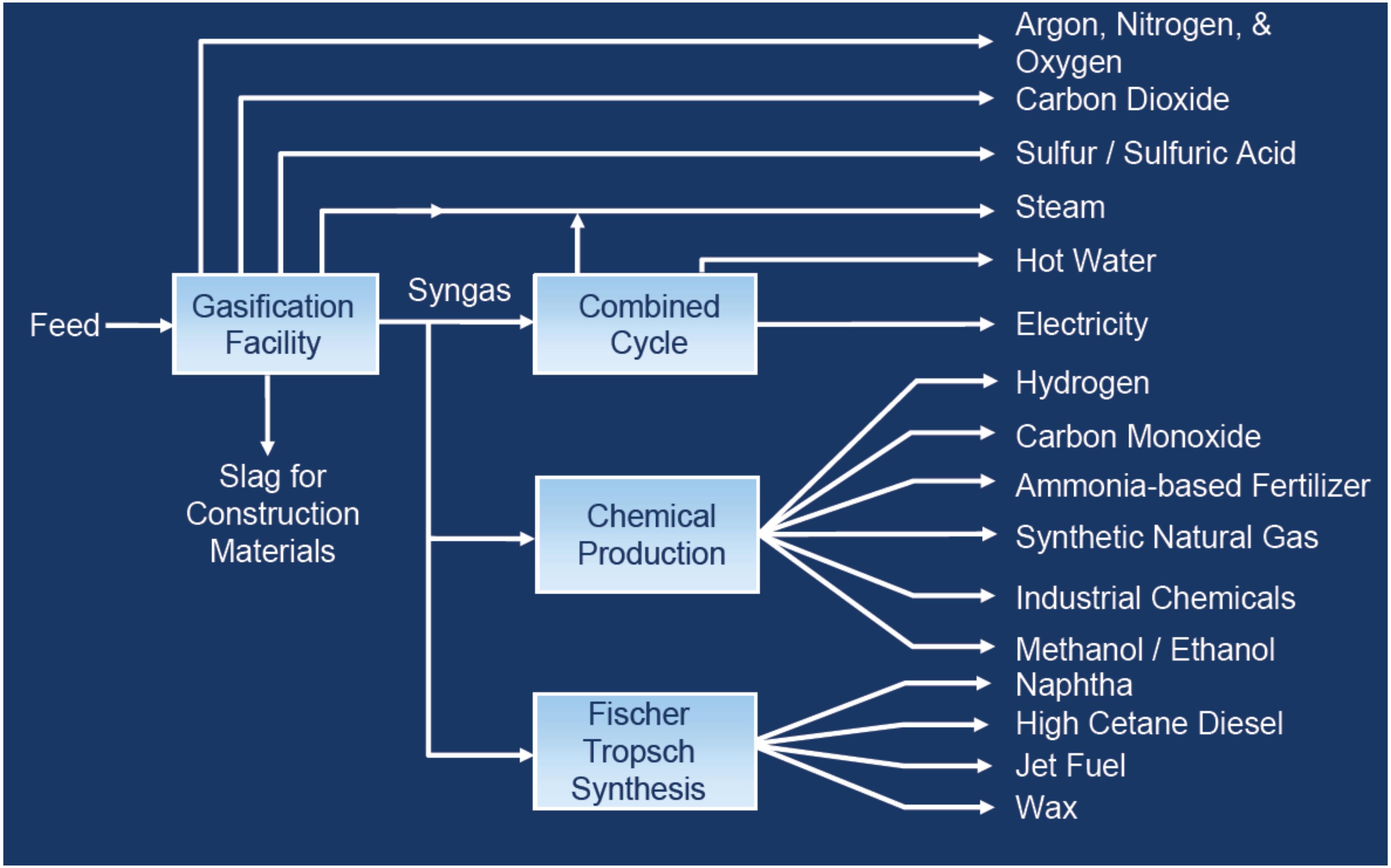
So what can you do with CO and H_2 ?

Building Blocks for Chemical Industry

Clean Electricity

Transportation Fuels (Hydrogen)

Gasification Products



Source: FLUOR®

Chemicals from Coal - Final Products

It is likely that you have recently used a product based on coal gasification

Acetic Anhydride
Acetic Acid

Source: Eastman Gasification Services Company

Gasification Chemistry

Gasification with Oxygen

$C + {}^{1}/_{2}\, O_2 \longleftrightarrow CO$

Combustion with Oxygen

$C + O_2 \longleftrightarrow CO_2$

Gasification with Carbon Dioxide

$C + CO_2 \longleftrightarrow 2CO$

Gasification with Steam

$C + H_2O \longleftrightarrow CO + H_2$

Gasification with Hydrogen

$C + 2H_2 \longleftrightarrow CH_4$

Water-Gas Shift

$CO + H_2O \longleftrightarrow H_2 + CO_2$

Methanation

$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$

Gasifier Gas Composition (Vol %)

H_2	25 - 30
CO	30 - 60
CO_2	5 - 15
H_2O	2 - 30
CH_4	0 - 5
H_2S	0.2 - 1
COS	0 - 0.1
N_2	0.5 - 4
Ar	0.2 - 1
NH_3 + HCN	0 - 0.3

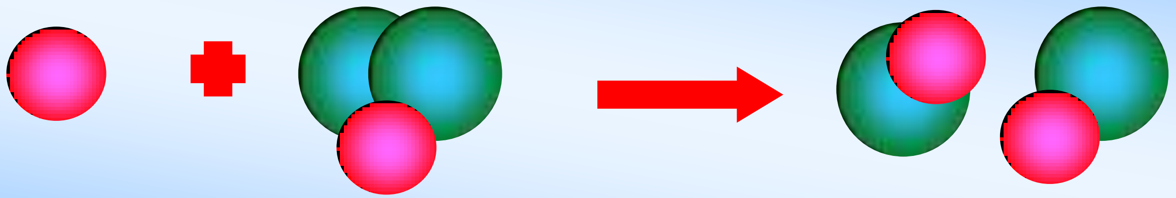
Ash/Slag/PM

Chemical Reactions in Coal Gasification

Reaction	Reaction heat, (kJ/mol)	Process
	Solid-gas reactions (liquid H_2O)	
$C + O_2 \rightarrow CO_2$	– 393.4	Combustion
$C + 2H_2 \rightarrow CH_4$	– 74.9	Hydrogasification
$C + H_2O \rightarrow CO + H_2$	+ 175.1	Steam-carbon
$C + CO_2 \rightarrow 2CO$	+ 172.3	Boudard
	Gas-phase reaction	
$CO + H_2O \rightarrow H_2 + CO_2$	2.7	Water-gas shift
$CO + 3H_2 \rightarrow CH_4 + H_2O$	– 249.9	Methanation

Examples of Important Reactions

Examples of Important Chemical Reactions in Coal Gasification



$C + CO_2 \rightarrow 2CO$

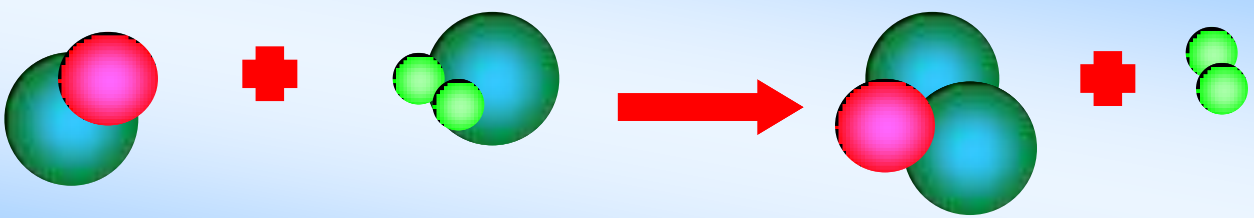
$\Delta H° \times 10^3$, 25°C

172.3 kJ/mol

$C + H_2O \rightarrow CO + H_2$

$\Delta H° \times 10^3$, 25°C

175.1 kJ/mol



$CO + H_2O \rightarrow CO_2 + H_2$

$\Delta H° \times 10^3$, 25°C

2.7 kJ/ mol

Combustion Chemistry

Combustion with Oxygen

$$C + O_2 \longleftrightarrow CO_2$$

$${}^{1}/_{2}\, O_2 + H_2 \longleftrightarrow H_2O$$

Combustion Gas Composition (Vol %)

CO_2	13.5
H_2O	9.8
SO_2	0.4
N_2	73.2
O_2	3.2

Ash/Slag/PM

Chemical Reactions in Coal Combustion

Reaction	Reaction heat, kJ/mol (liquid H_2O)
$C + CO_2 \rightarrow 2CO$	+ 172.3
$C + H_2O \rightarrow CO + H_2$	+ 175.1
$C + O_2 \rightarrow CO_2$	– 393.4
$C + ½ O_2 \rightarrow CO$	– 110.5
$CO + H_2O \rightarrow H_2 + CO_2$	+ 2.7
$CO + ½ O_2 \rightarrow CO_2$	– 282.9

Examples of Important Reactions

Examples of Important Chemical Reactions in Coal Combustion

C + O_2 → CO_2

$\Delta H° \times 10^3$, 25°C

- 393.4 kJ/ mol

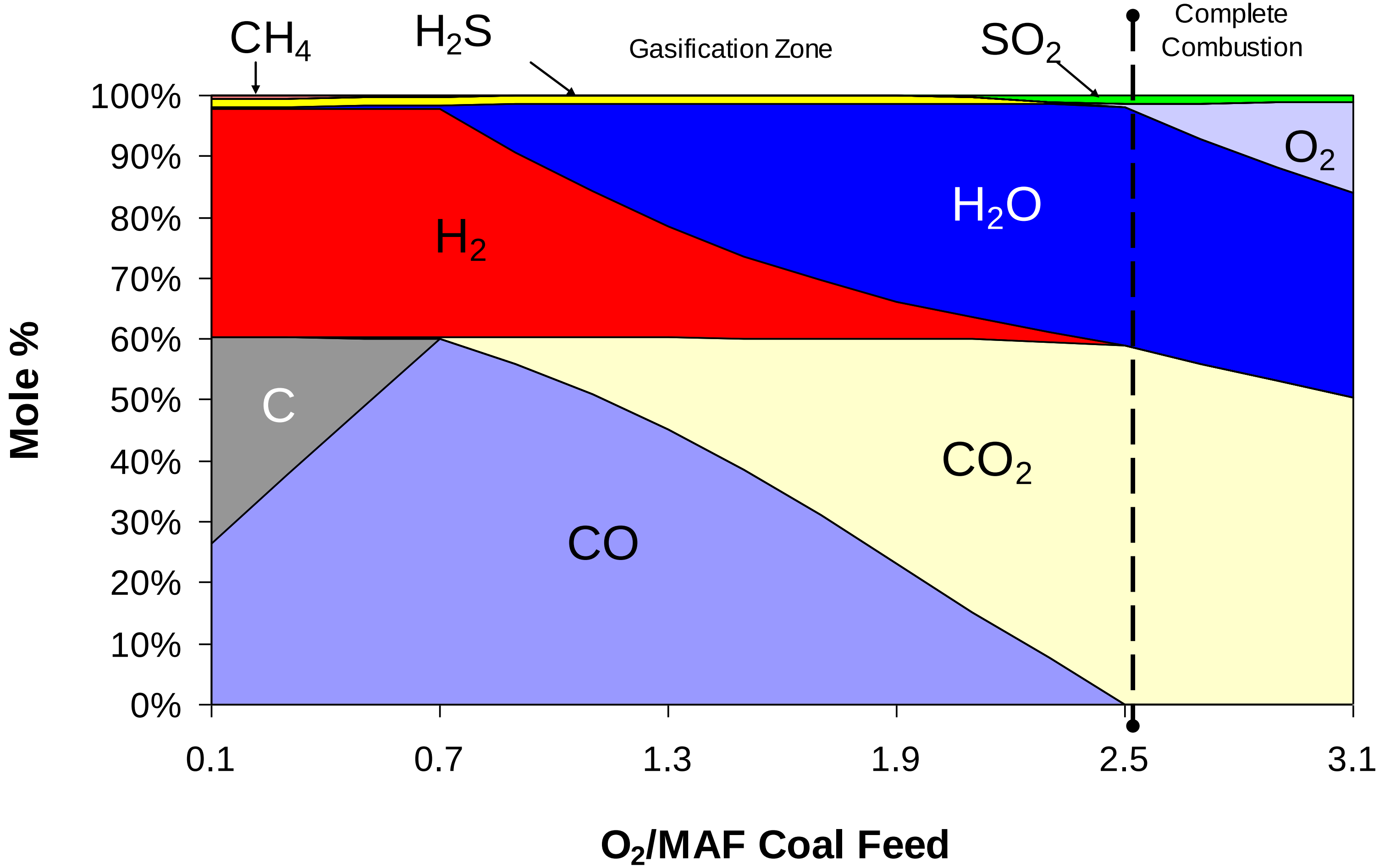
H_2 + 1/2 O_2 → H_2O

$\Delta H° \times 10^3$, 25°C

- 285.6 kJ/ mol

Gasification Phase Diagram

An Example



Coal: Illinois #6, Dry Feed

Fundamental Comparison of IGCC with Advanced PC-Fired Plant

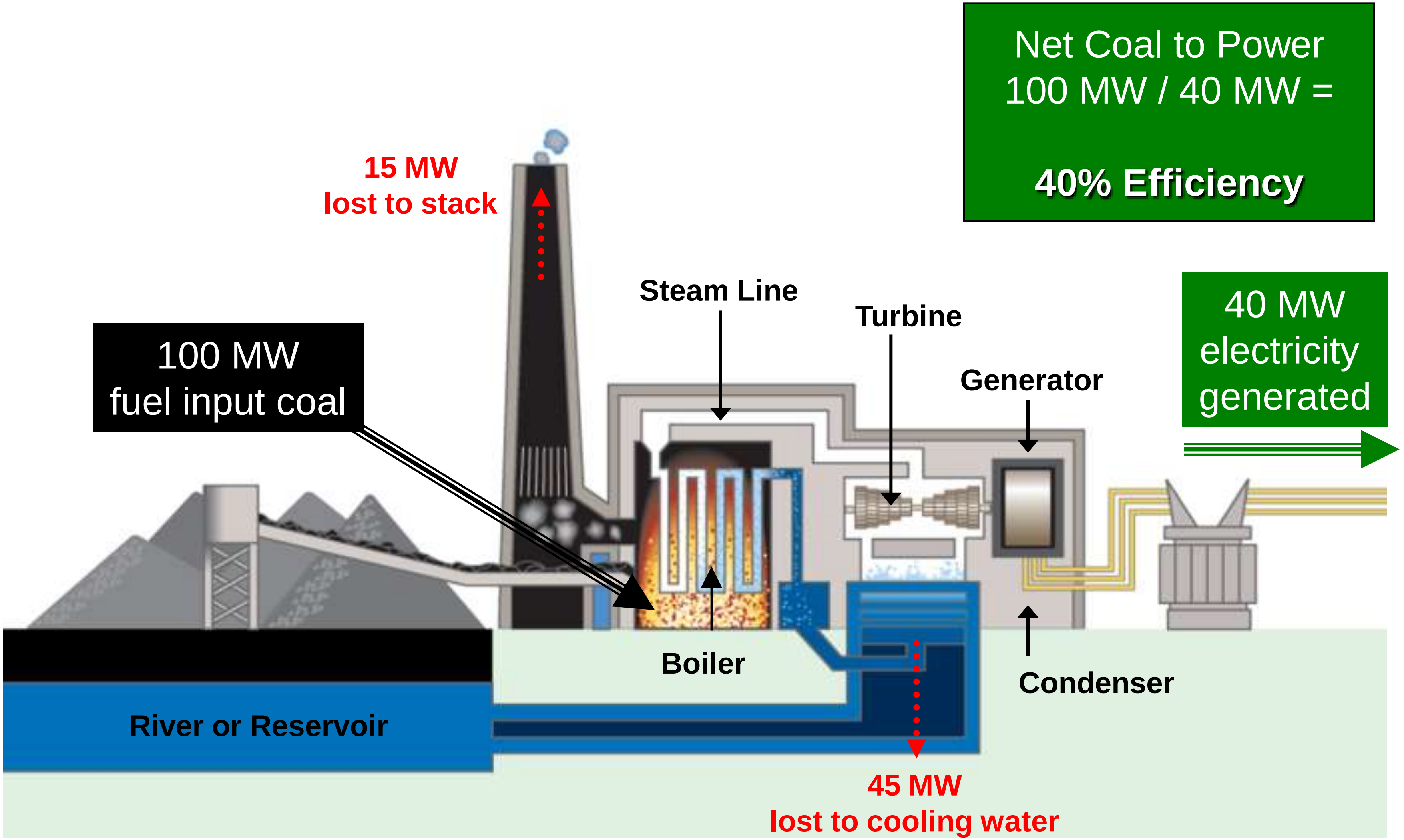
	IGCC	PC
• Operating Principles	Partial Oxidation	Full Oxidation
• Fuel Oxidant	Oxygen	Air
• Temperature	≤ 3000 °F	≤ 3200 °F
• Pressure	400-1000 psi	Atmospheric
• Sulfur Control	Concentrate Gas	Dilute Gas
• Nitrogen Control	Not Needed	Pre/Post Combustion
• Ash Control	Low Vol. Slag	Fly/Bottom Ash
• Trace Elements	Slag Capture	ESP/Stack
• Wastes/By-products	Several Markets	Limited Markets
• Efficiency (HHV)	36-41%	35-40%

Comparison of Air Emission Controls: *PC vs. IGCC*

	Sulfur	*NO_x*	*PM*	*Mercury*
PC	FGD system	Low-NO_x burners and SCR	ESP or baghouse	Inject activated carbon
IGCC	Chemical and/or physical solvents	Syngas saturation and N_2 diluent for GT and SCR	Wet scrubber, high temperature cyclone, barrier filter	Pre-sulfided activated carbon bed

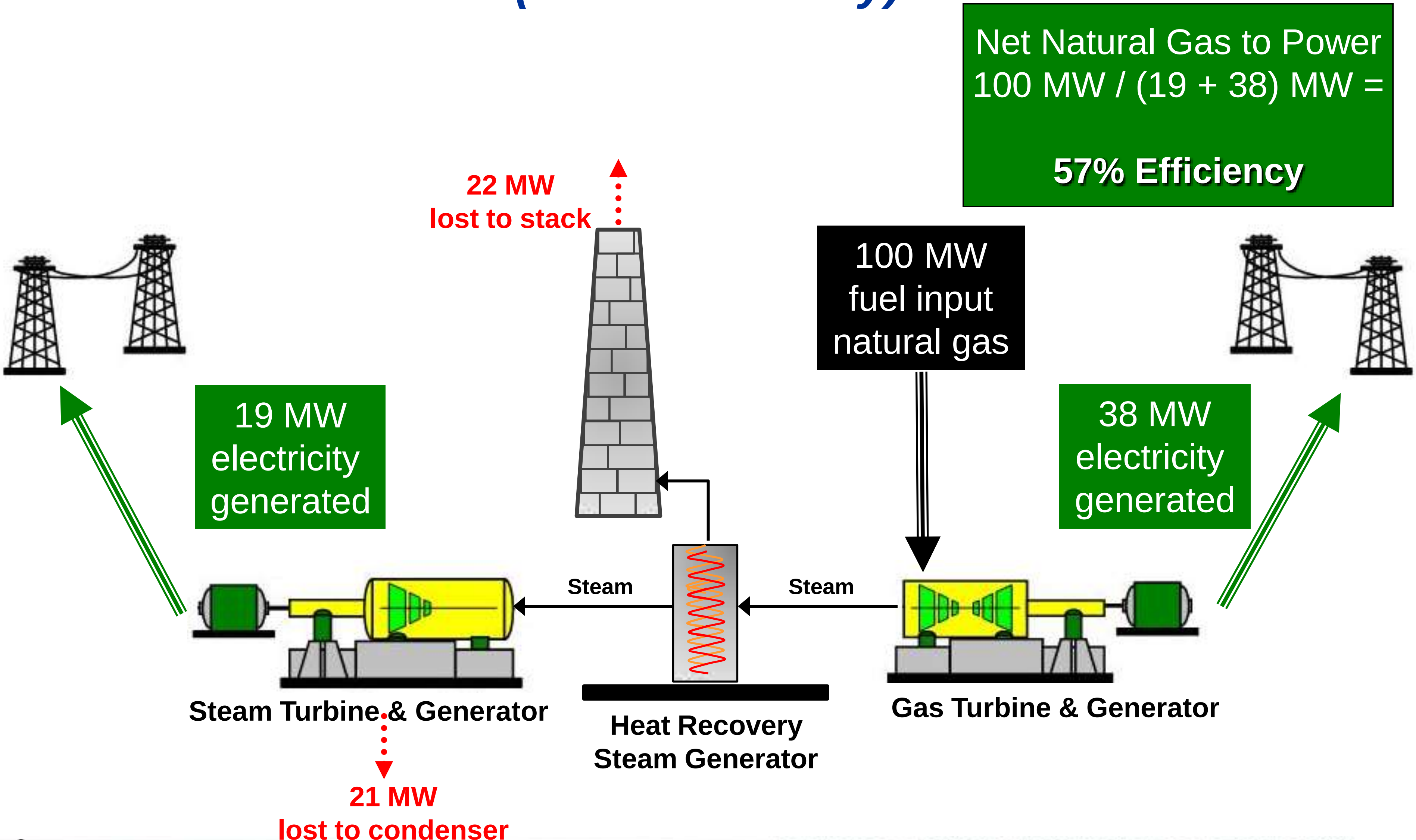
Steve Jenkins 2007 GTC Conference http://www.gasification.org/Docs/2007_Papers/22JENK.pdf

Conventional Coal Plant
(Illustration only)



Source: EPRI

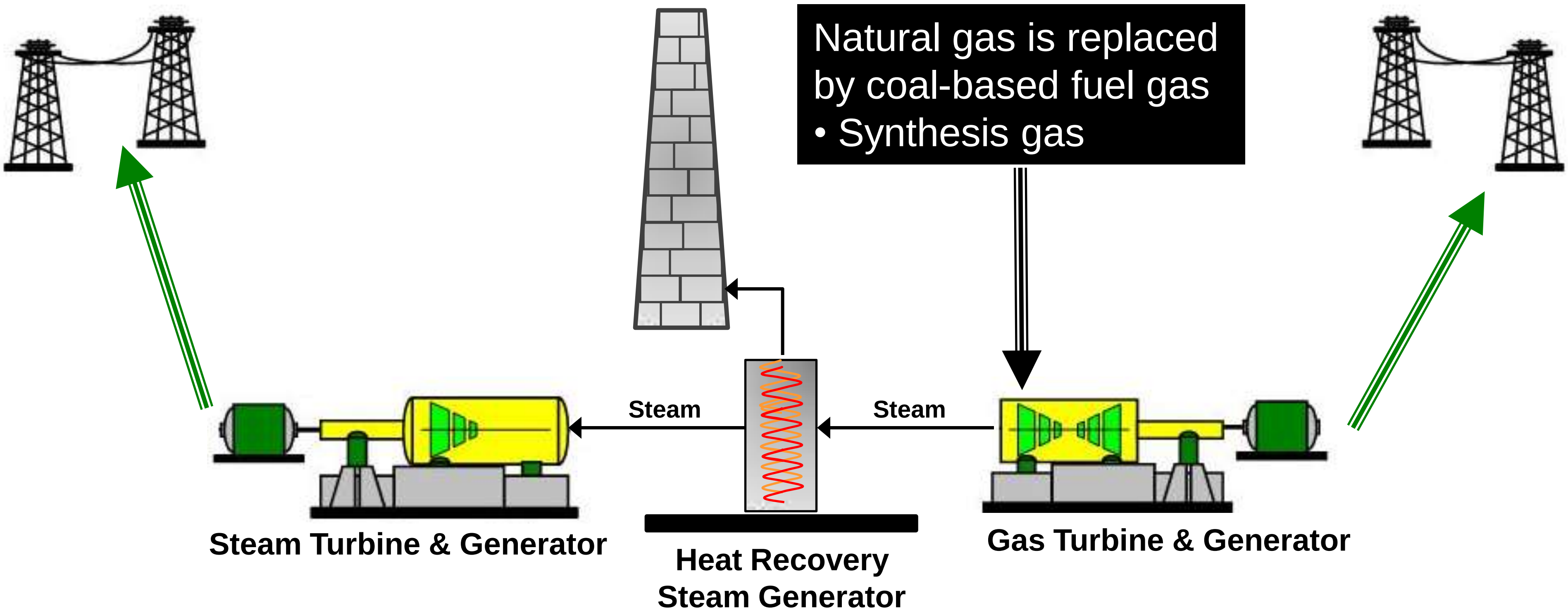
Combined Cycle
(Illustration only)



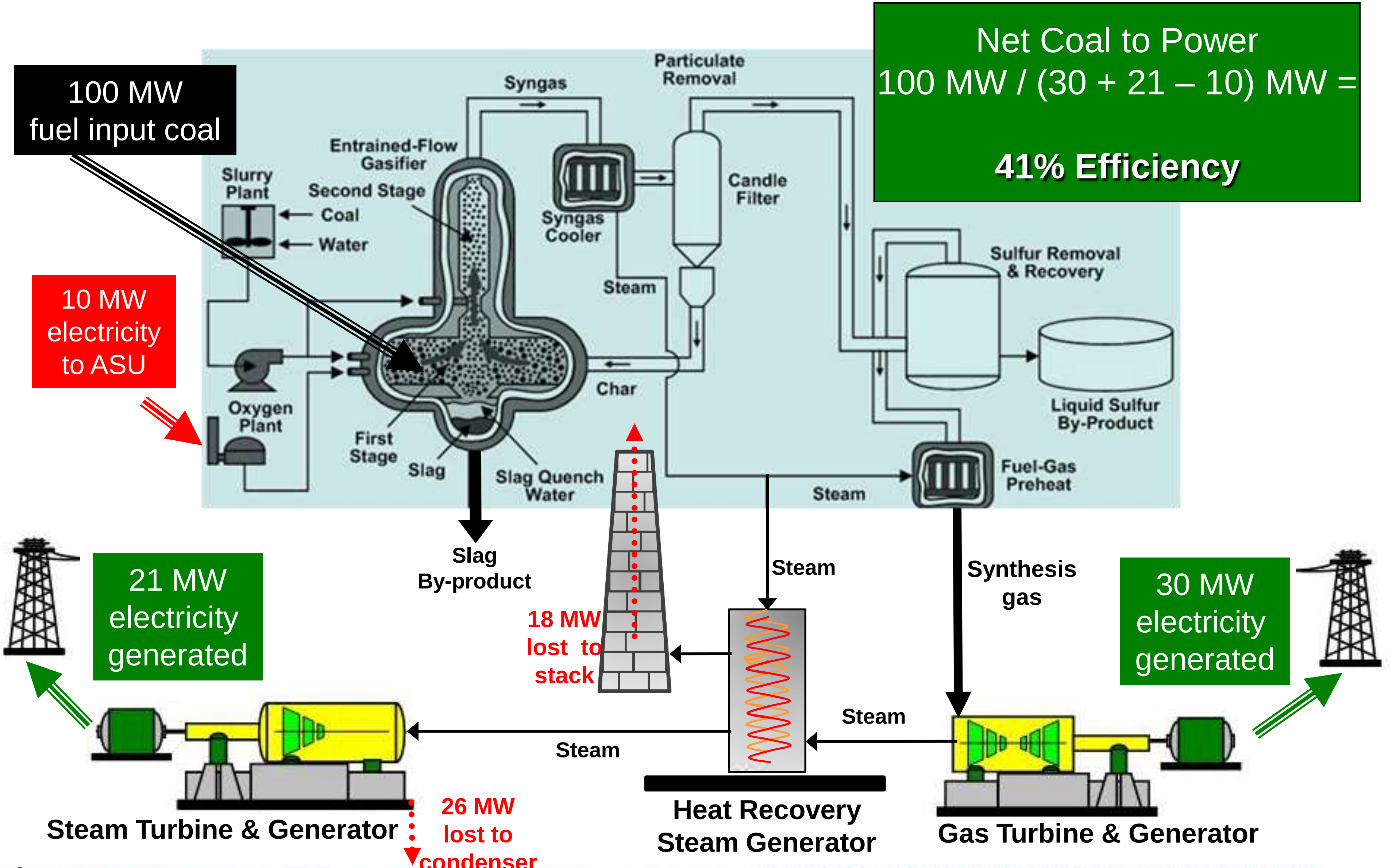
Coal-Based IGCC Power Plant

Gasification Island
- Converts coal to synthesis gas
- Cleans & conditions synthesis gas

Natural gas is replaced by coal-based fuel gas
- Synthesis gas



Coal-Based IGCC Power Plant



Gasification-Based Energy Conversion Systems

RESOURCES

Air/Oxygen

Coal

Biomass

Petroleum Coke

Heavy Oil

Refinery Wastes

MSW

Orimulsion

Other Wastes

GASIFIERS

OXYGEN-BLOWN

Entrained Flow
GE Energy, E-Gas, Shell, Prenflo, Noell, TPRI, OMB

Fluidized Bed
HT Winkler, U-Gas

Moving Bed
British Gas Lurgi (BGL)
Lurgi (Dry Ash)

Transport Reactor
KBR

AIR-BLOWN

Fluidized Bed
HT Winkler, GTI U-Gas, KRW

Sprouting Bed
British Coal, Foster Wheeler

Entrained Flow
Mitsubishi

Transport Reactor
KBR

ENVIRONMENTAL CONTROL

Particulate Removal and Recycle
Filtration,
Water Scrubbing

Chloride and Alkali Removal
Water Scrubbing

Acid Gas Removal
Amine Processes
Rectisol, Selexol

COS Hydrolysis

Sulfur Recovery
Claus Process
SCOT Process
Sulfuric Acid Plant

Water Treatment
Process Water, BFW

Tail Gas Treating

Turbine NOx Control
Nitrogen/Steam Dilution
SCR

Syngas Mercury Capture

Syngas CO_2 Capture

ENERGY CONVERSION

Gas Turbine

Heat Recovery Steam Generator (HRSG)

Steam Turbine

Boiler

Syngas Conversion to Fuels & Chemicals

Catalytic Conversion

Shift Conversion

Fischer-Tropsch

Fuel Cell

H_2 Turbine

PRODUCTS

Steam

Electric Power

Liquid Fuels

Chemicals

Methanol

Hydrogen

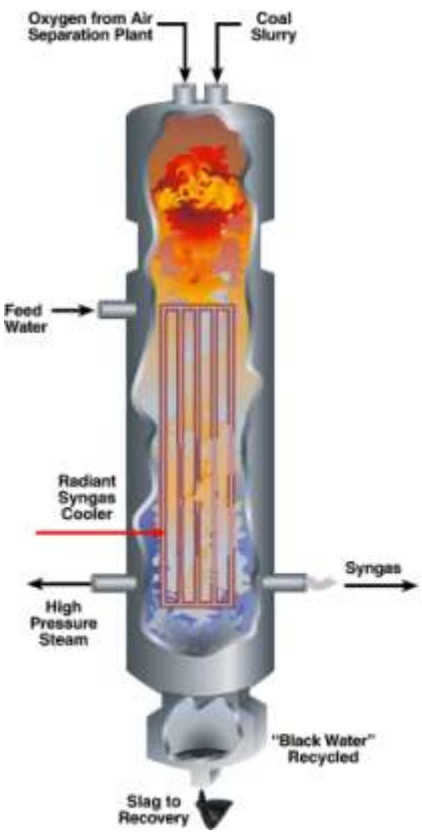
Ammonia/ Fertilizers

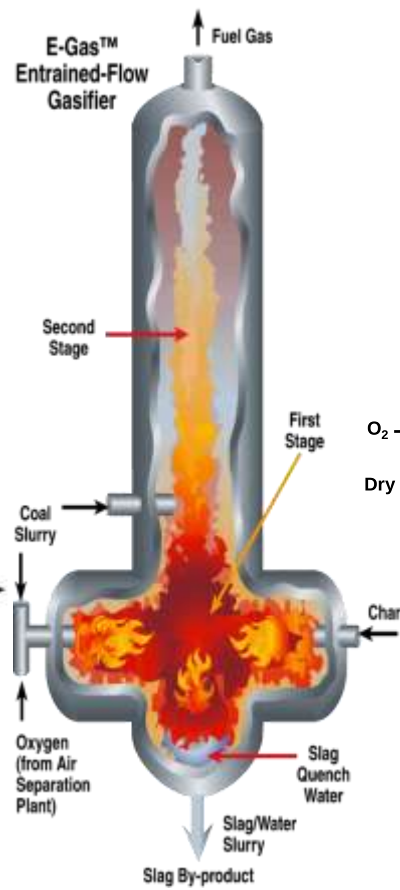
Slag

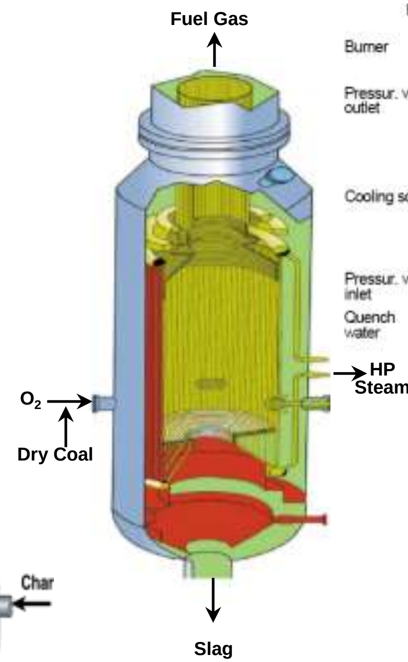
Sulfur/ Sulfuric Acid

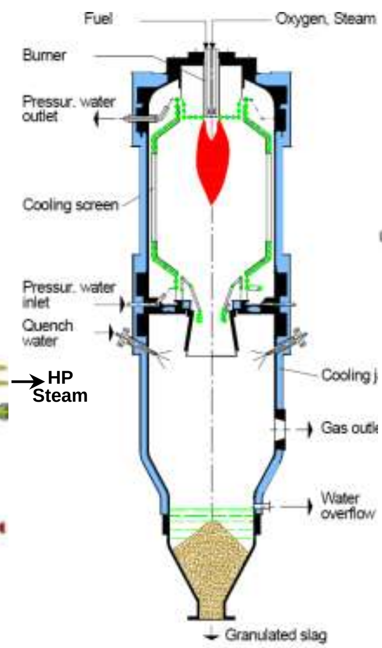
Gasifiers

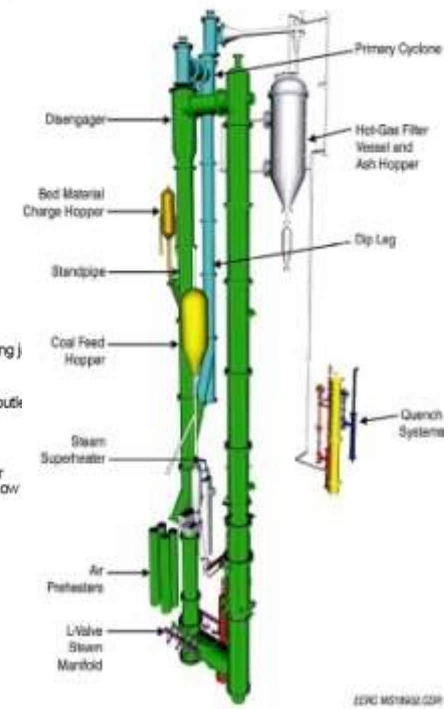
GE Energy *(Chevron-Texaco)*	ConocoPhillips E-Gas	Shell SCGP	Siemens *(GSP/Noell)*	KBR Transport





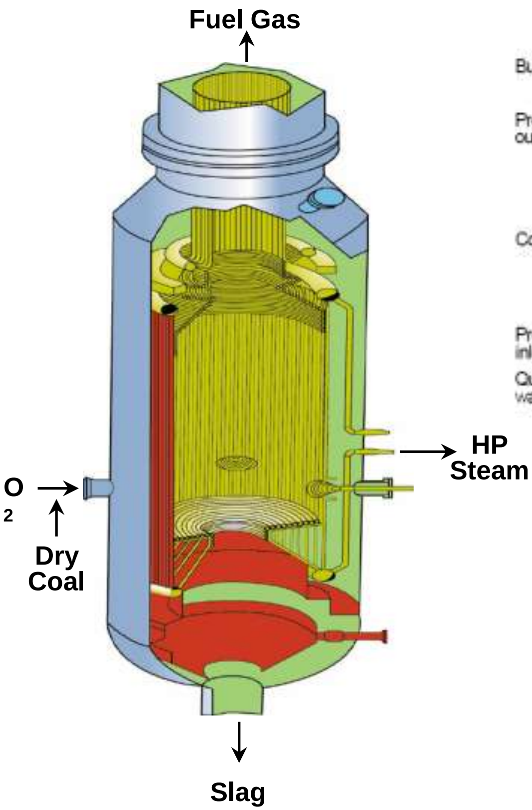




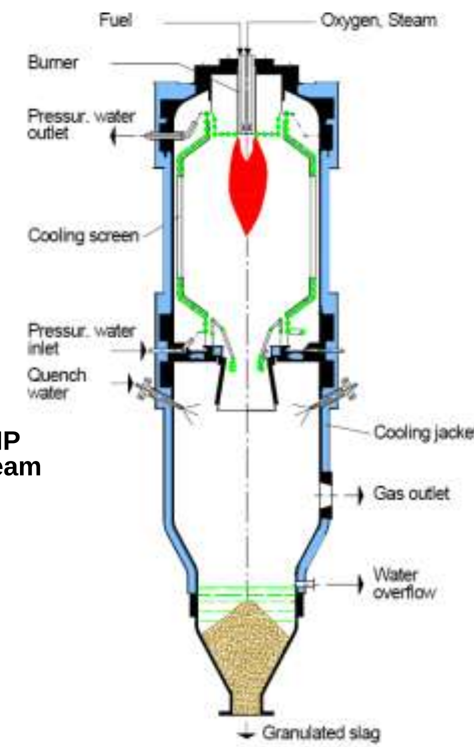


Gasifiers for Low Rank Coal

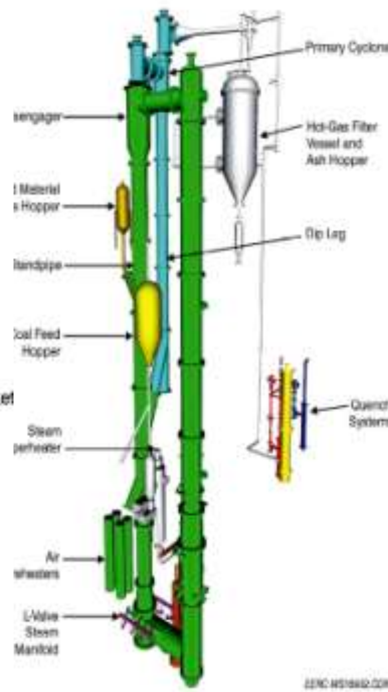
Shell SCGP



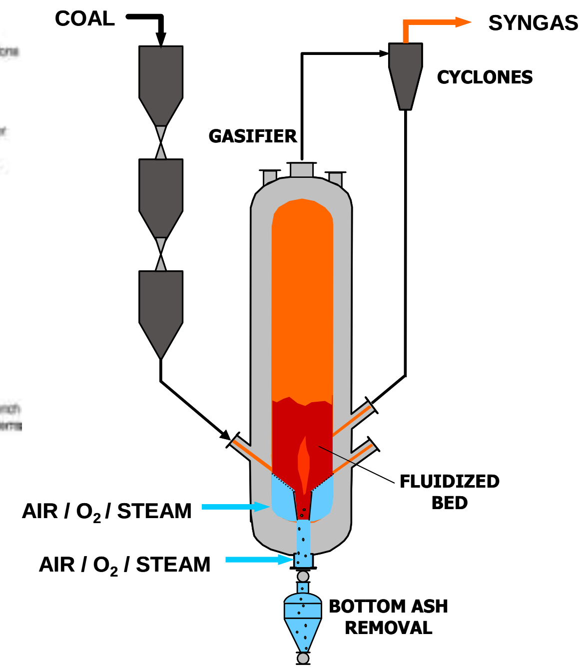
Siemens *(GSP/Noell)*



KBR Transport

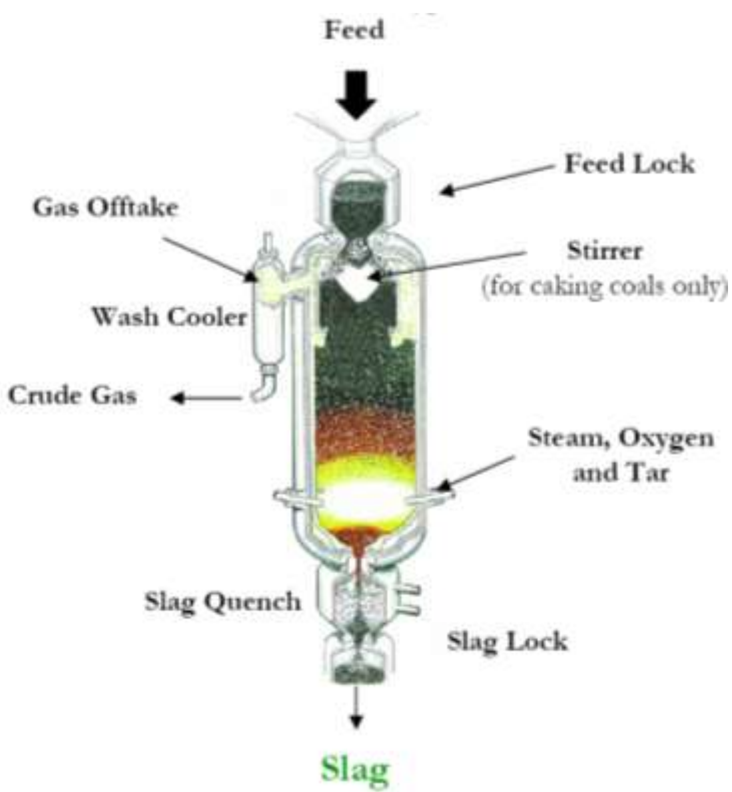


GTI Fluid Bed

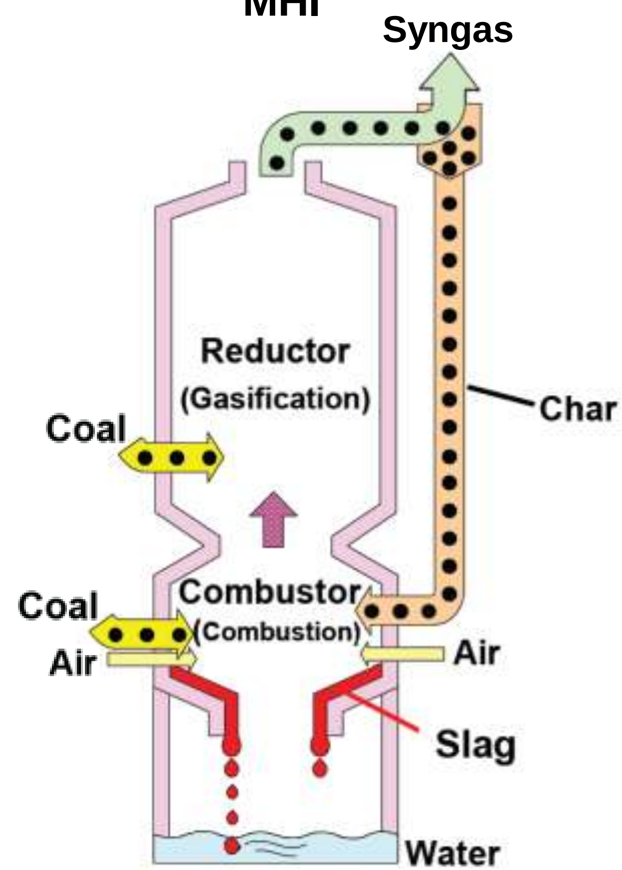


Gasifiers for Low Rank Coal *(continued)*

BGL

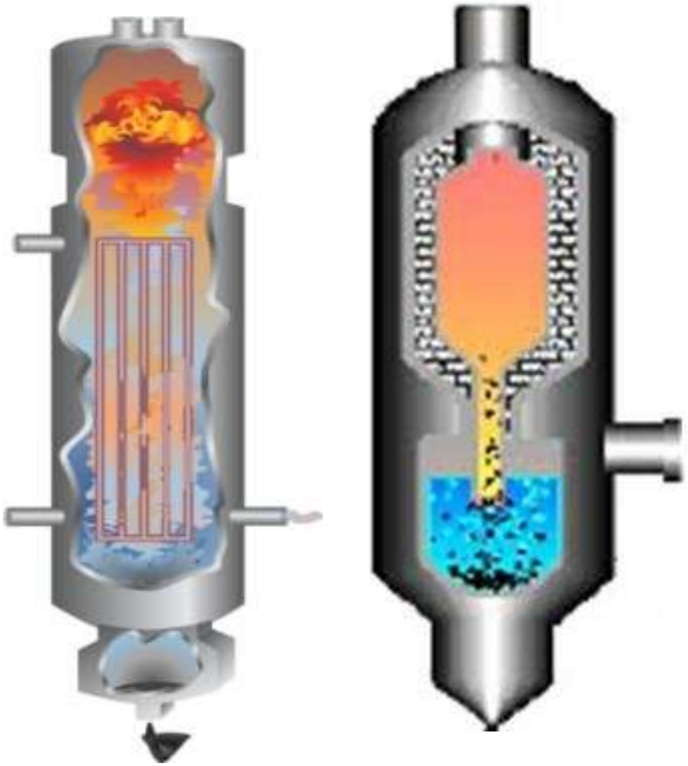


MHI



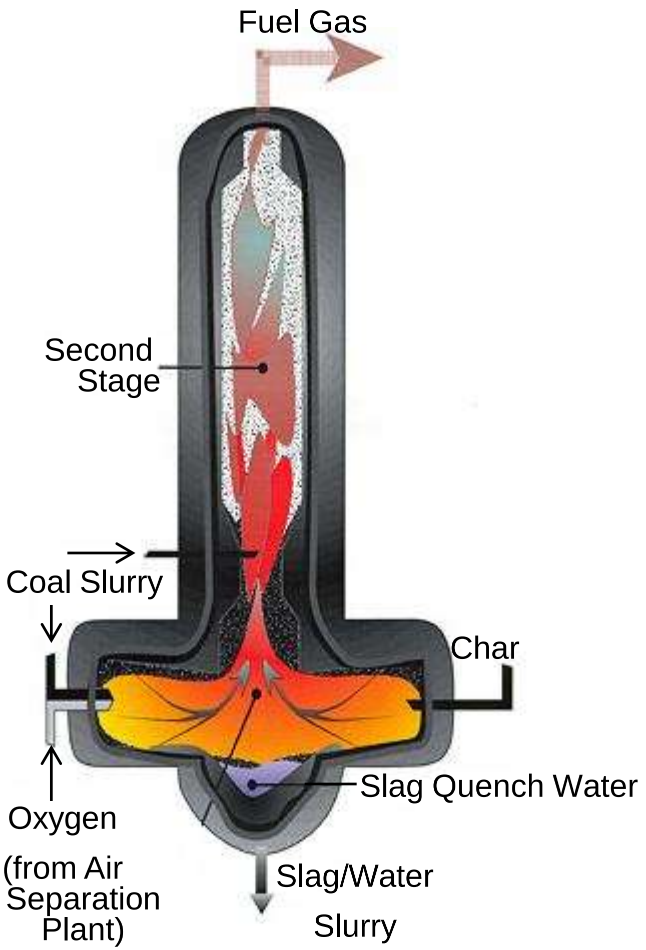
GE Energy Gasifier

- **Coal-water slurry feed**
- **Entrained-flow**
- **Oxygen-blown**
- **Refractory-lined gasifier**
- **Two versions offered**
  - Radiant cooler
  - Quench
- **Slagging**
- **Good for bituminous coal, pet coke, or blends of pet coke and low-rank coals**
- **EPC alliance with Bechtel for guarantees on total IGCC plant**
- **64 Plants operating**
  - 15,000 MWth Syngas
- **10 Plants in planning**



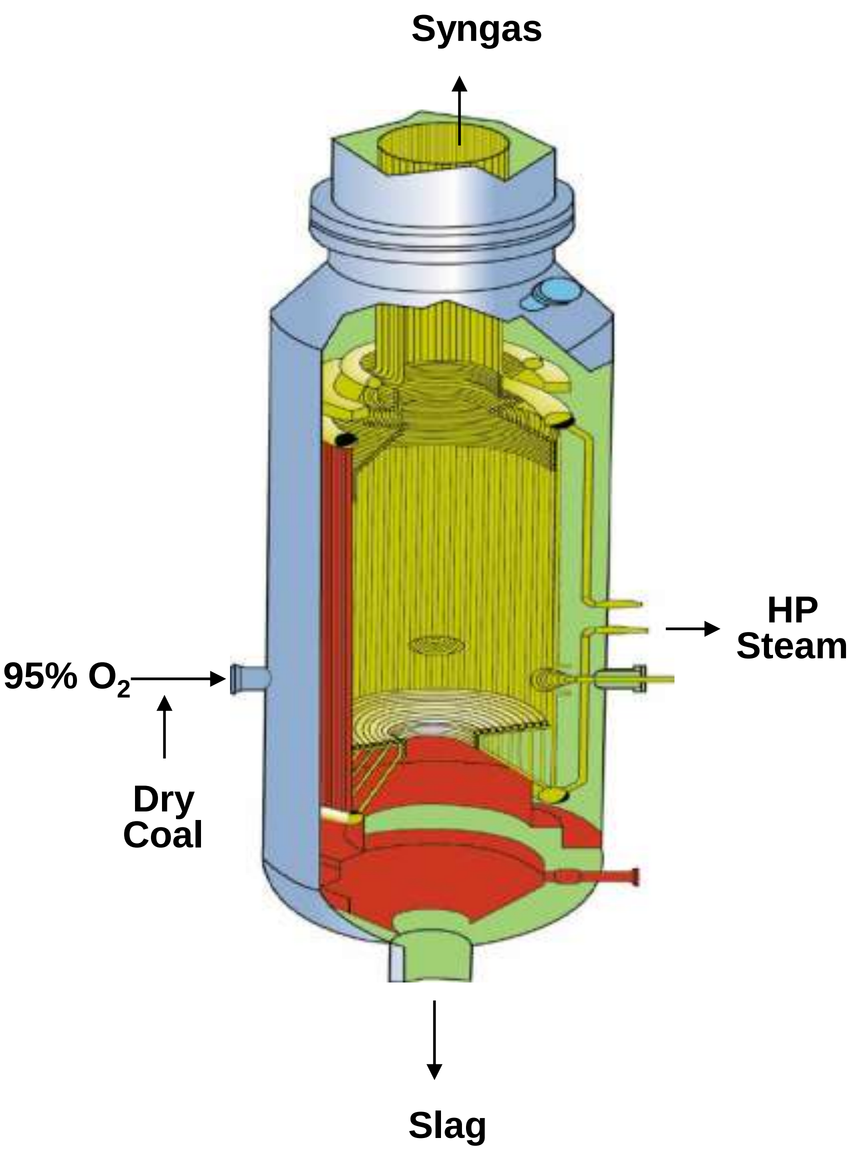
ConocoPhillips (E-Gas) Gasifier

- **Entrained-flow**
- **Two-stage gasifier**
  - 80% of feed to first stage (lower)
  - Advanced E-STR gasifier feeds 100% to second stage (upper)
- **Coal-water slurry feed**
- **Oxygen-blown**
- **Refractory-lined gasifier**
- **Continuous slag removal system, dry particulate removal**
- **Good for a wide range of coals, from pet coke to PRB to Bituminous and blends**
- **Project specific EPC and combined cycle supplier alliances**
- **1 Plant operating - 590 MWth Syngas**
- **4 Plants in planning**



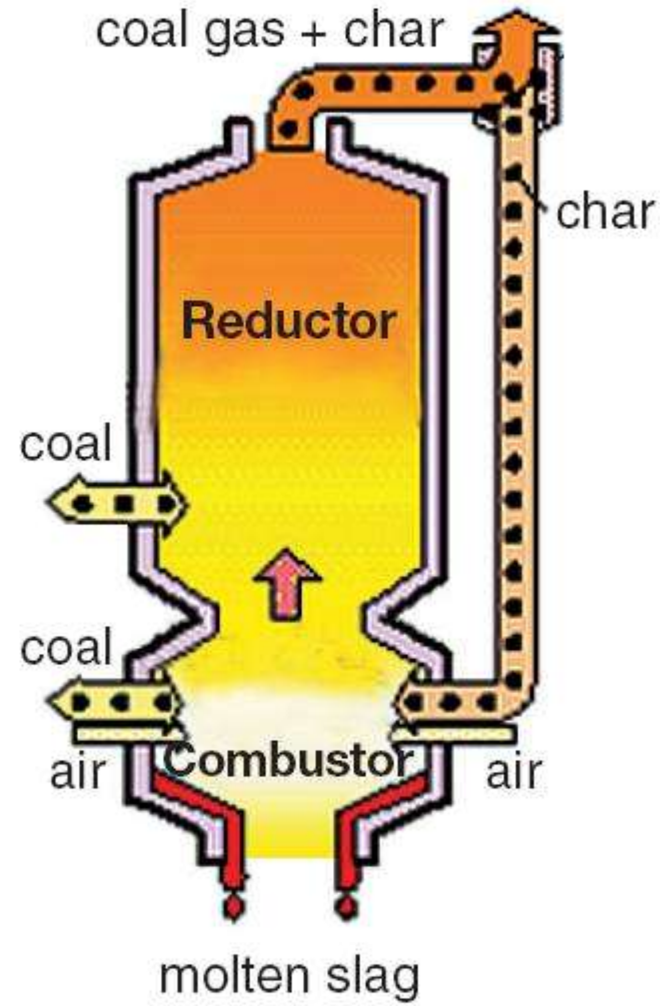
Shell Gasifier

- **Entrained flow gasifier**
- **Dry feed**
  - coal is crushed and dried
- **Oxygen-blown**
- **Waterwall in gasifier**
- **Good for wide variety of feedstocks, from pet coke to low-rank coals**
- **First plants in China operating**
- **8,500 MWth Syngas**
- **Several Plants in planning**



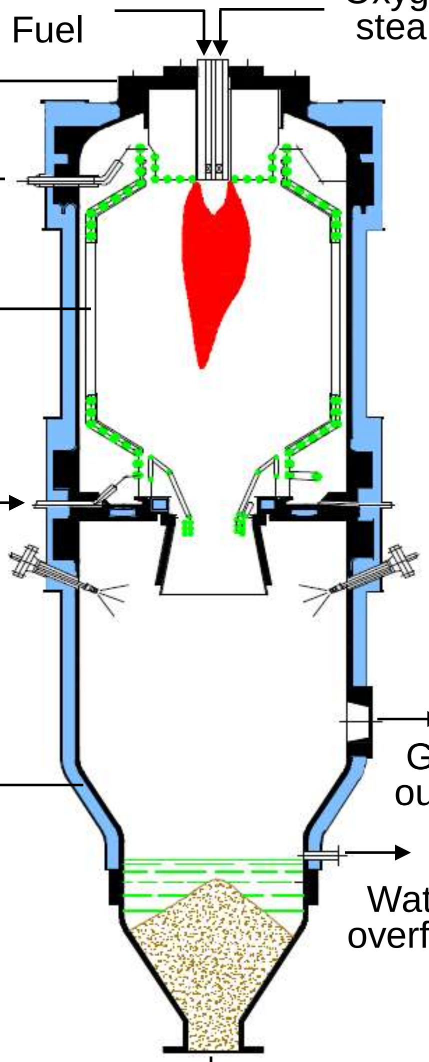
Mitsubishi Gasifier

- Entrained bed
- Dry feed system
- Suitable for low rank coal with high moisture content
- Two-Stage feeding
- Air Blown
- Membrane waterwall
- Slagging
- Developed in the 80's by Central Research Institute of the Electric Power Industry Japan
- 1 Plant in planning
- 1 Demonstration plant in operation, 250 MWe, Nakoso, Japan, startup Sept 2007



Siemens GSP Gasifier

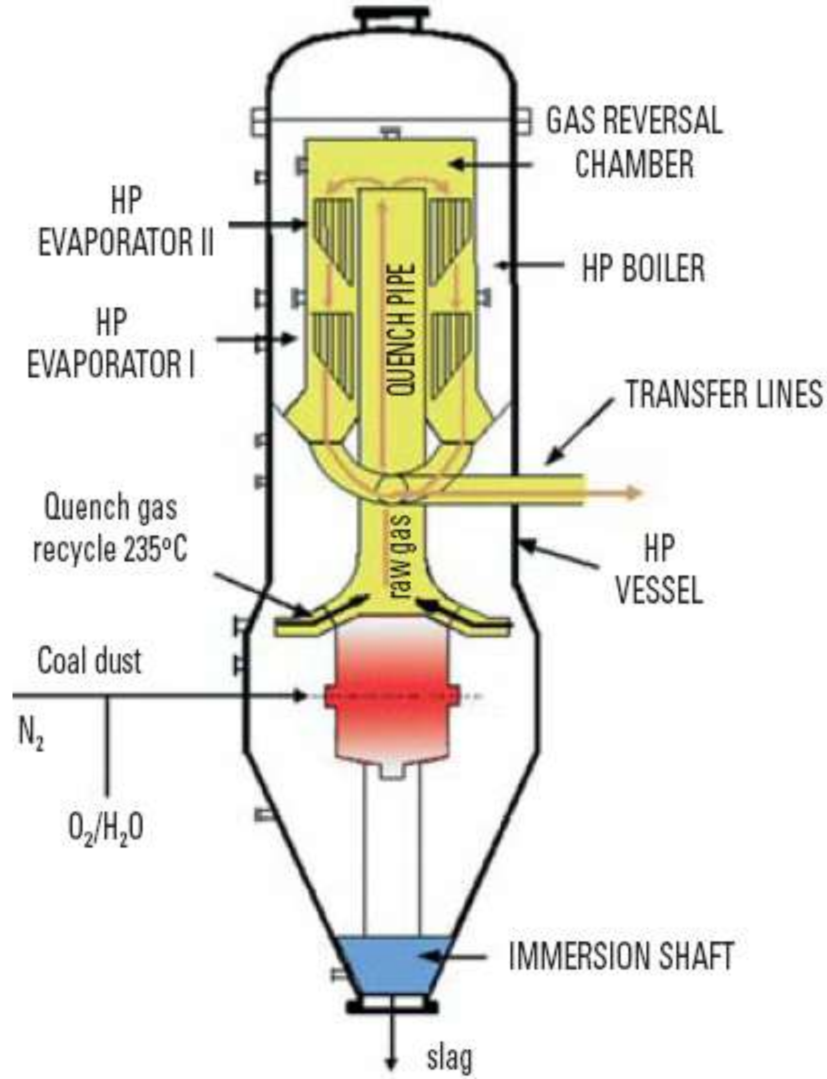
- **Entrained flow gasifier**
- **Dry feed**
- **Oxygen-blown**
- **Top fired reactor**
- **Waterwall screen in gasifier**
- **Good for a wide variety of feedstocks, from bituminous to low-rank coals**
- **Siemens provides gasification island and power block**
- **Freiberg Pilot Plants**
  - Cooling wall/screen
  - 3 MW & 5 MW
- **2 Industrial plants:**
  - Vřesová (oil), Schwarze Pumpe*
  - Secure Energy Decatur
    - Under construction
- **9 SFG-500 gasifiers on order or being manufactured**



*no longer operating

PRENFLO™ Gasifier/Boiler (PSG)

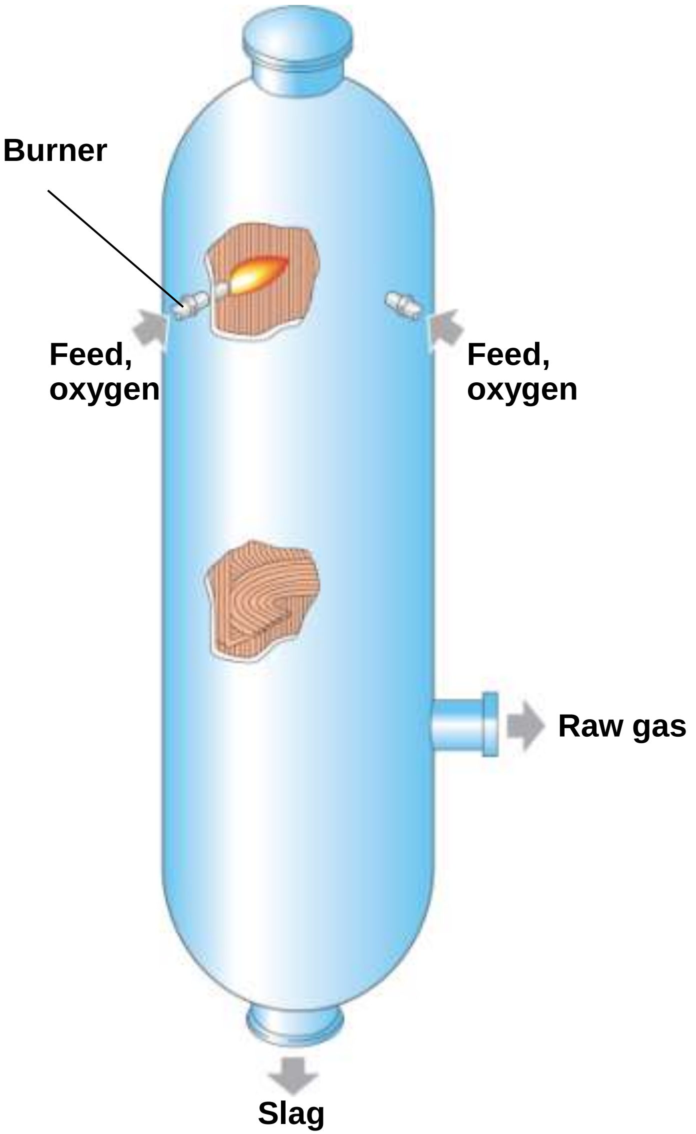
- **Pressurized entrained flow gasifier with steam generation**
- **Uhde**
- **Oxygen blown**
- **Dry feed system**
- **Membrane wall**
- **Waste heat boiler**
- **Able to gasify variety of solid fuels**
  - hard coal, lignite, anthracite, refinery residues, etc.
- **Demonstration plant Fürstenhausen, Germany (48 TPD)**
- **Used in world's largest solid-feedstock-based IGCC plant in Puertollano, Spain**



Integrated Gasification Combined Cycle Technology: IGCC It's Actual Application in Spain: ELCOGAS, Puertollano. Manuel Treviño Coca

PRENFLO™ Gasifier (PDQ)

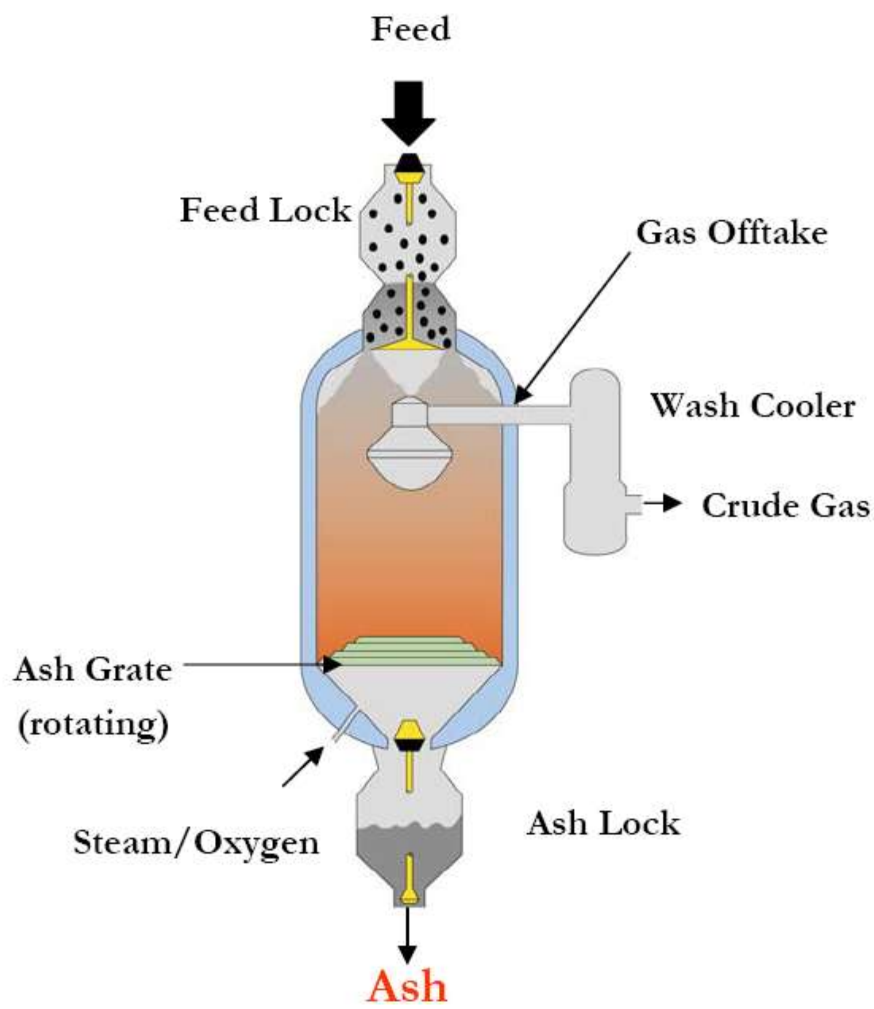
- **Pressurized entrained flow gasifier with direct quench (PDQ)**
- **License, EPCM, process guarantees by Uhde**
- **Oxygen blown**
- **Dry feed system**
- **Membrane wall**
- **Full water quench**
- **Able to gasify a wide variety of solid fuels**
  - hard coal, lignite, anthracite, refinery residues, etc.
- **Based on proven PSG design:**
  - Fürstenhausen, Germany
  - world's largest solid-feedstock-based IGCC plant in Puertollano, Spain
- **Compact design with significant cost savings**
- **First plants under design**



Lurgi Gasifier

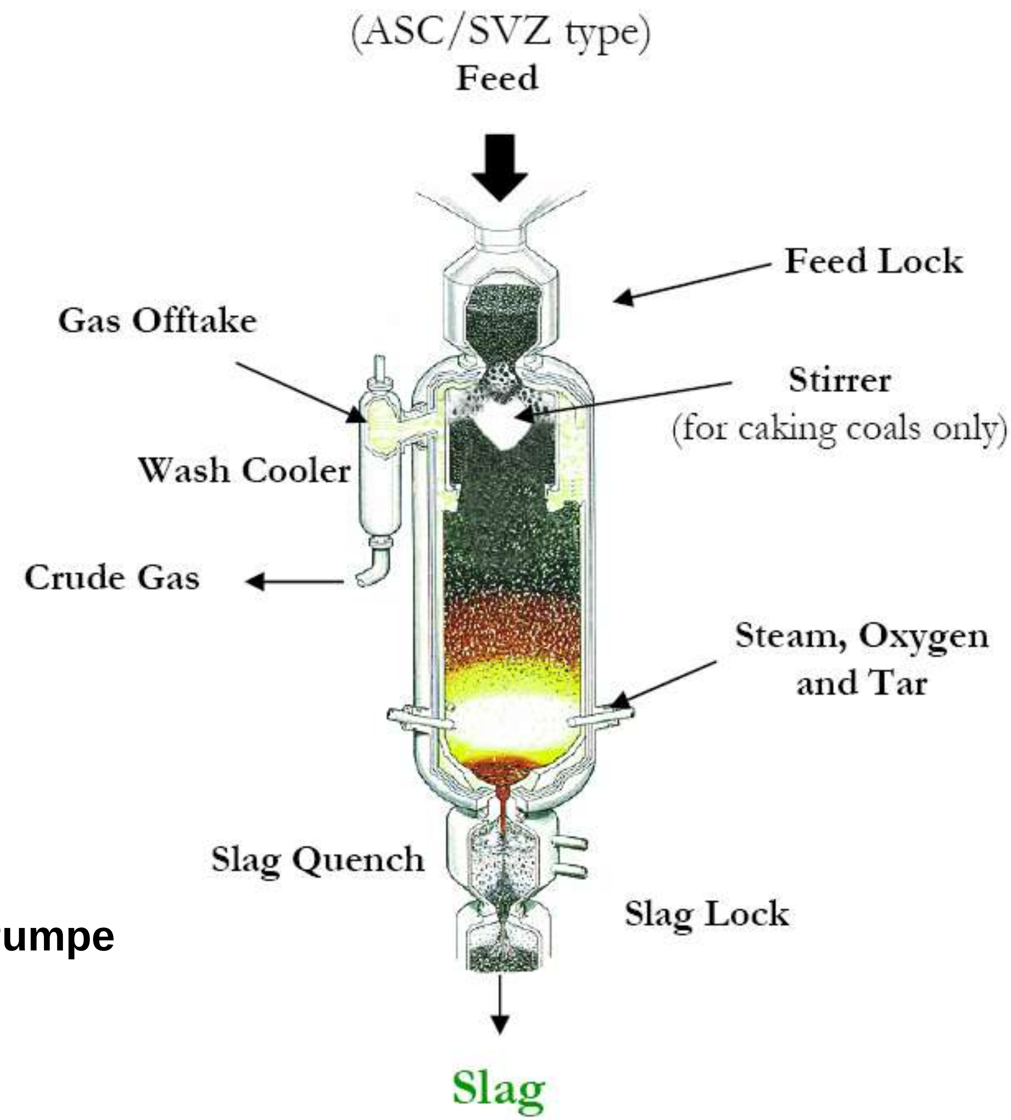
- **Moving bed gasifier**
- **Lock hoppers**
  - Distributor
  - Quench cooler
- **Dry feed system**
- **Dry bottom ash**
- **Extensive experience with low rank coals**
- **North Dakota/Sasol type**
- **8 Plants operating**
  - 18,600 MWth Syngas

(North Dakota/Sasol type)



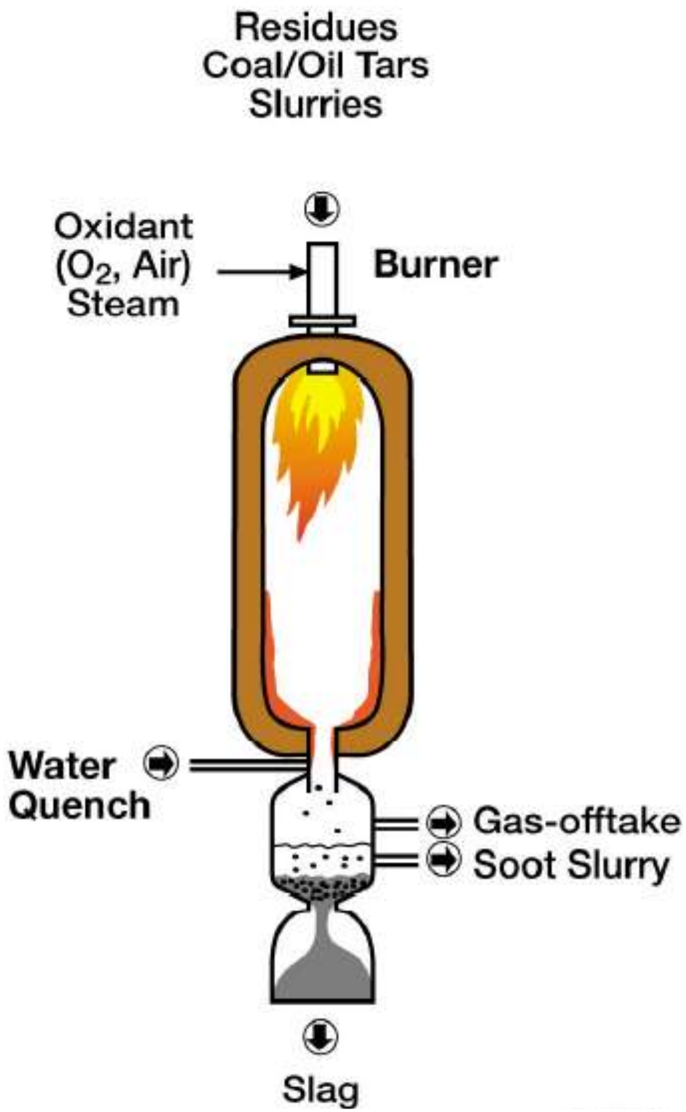
British Gas/ Lurgi (BGL) Gasifier

- Moving bed gasifier
- "Slagging" version of Lurgi
- Dry feed
- Oxygen-blown
- Refractory-lined gasifier
- Good for wide range of coals
- Opportunity fuel blends
  - RDF, tires, wood waste
- Modular design
- Allied Syngas build, own and operate in North American
- Demonstration plant
  - Westfield 1986 – 1990
  - 500 TPD
- 1 Plant in planning
- 1st Commercial plant Schwarze Pumpe
  - operated 2000 -2005
  - BGL-1000



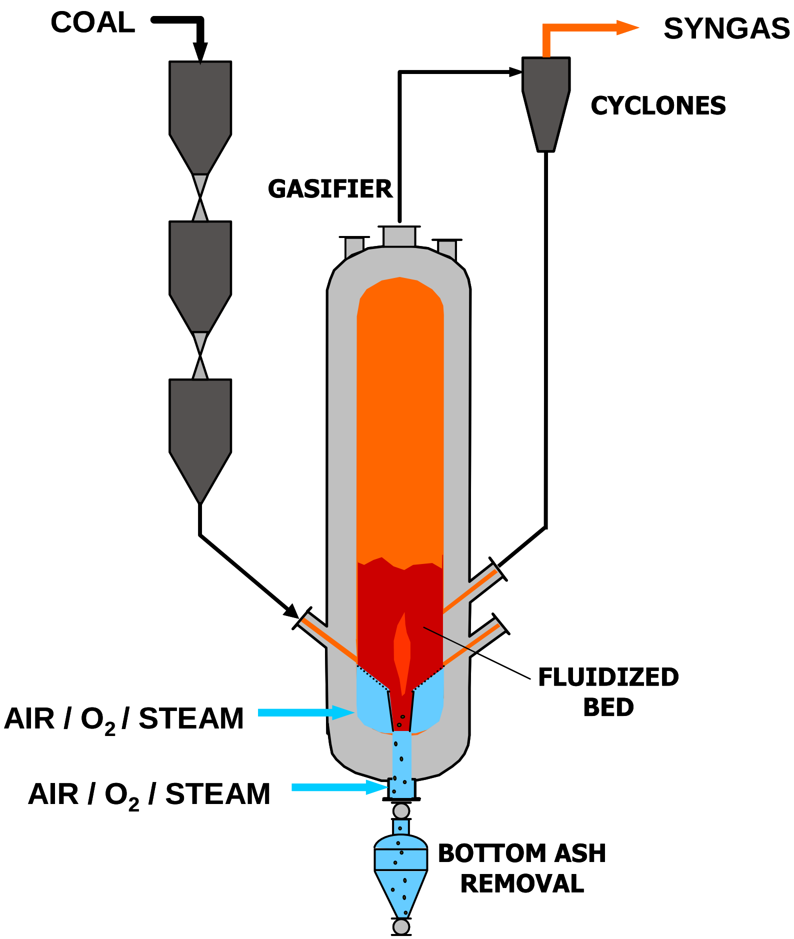
Multi Purpose (MPG) Gasifier

- **Moving bed gasifier**
- **Oxygen-blown**
- **Good for wide range of feedstocks**
  - Petcoke/ coal slurries and waste
- **Quench configuration for coal/petcoke feedstock**
- **MPG technology developed from Lurgi's fixed-bed gasification process**
- **"Reference plant" (oil)**
  - Schwarze Pumpe in operation since 1968



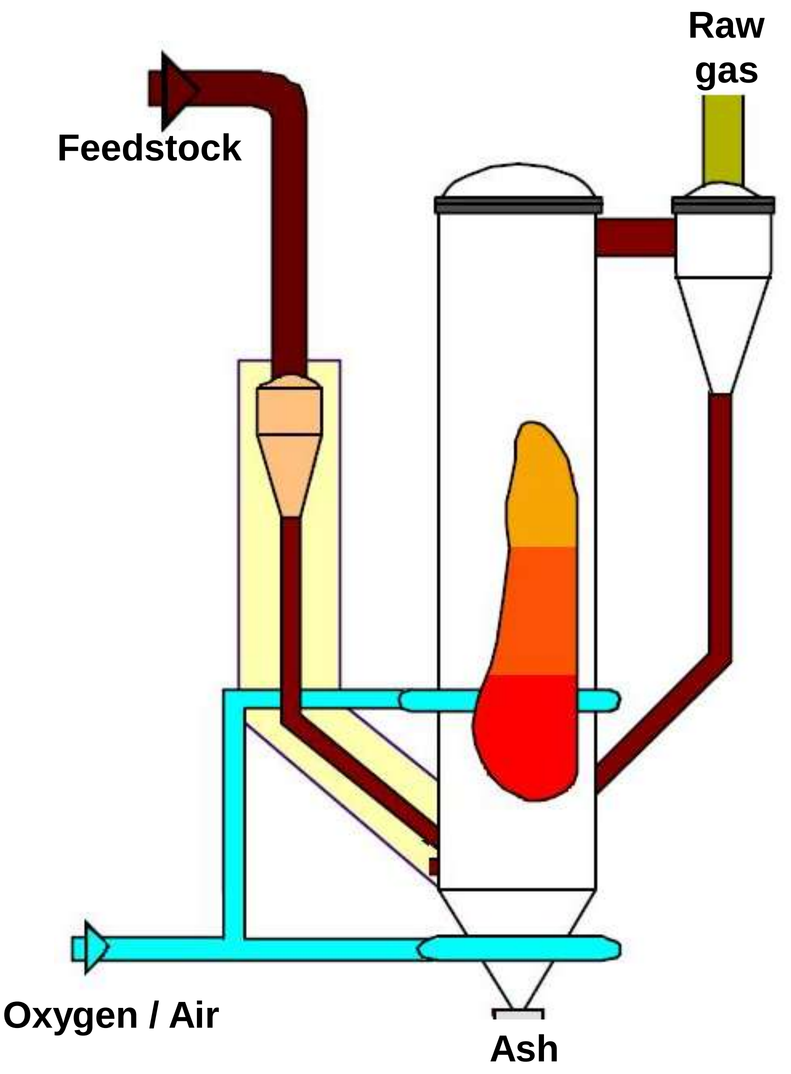
GTI (U-Gas) Gasifier

- **Fluidized bed gasifier**
- **Dry feed system**
- **Coal and coal/biomass blends**
- **Highly efficient**
- **Air or oxygen blown**
- **Non-slagging/bottom ash**
- **30 year license agreement with Synthesis Energy Systems (SES)**
- **20+ years experience including plants in Shanghai and Finland**
- **2 Plants in operation**
  - 520 MWth Syngas



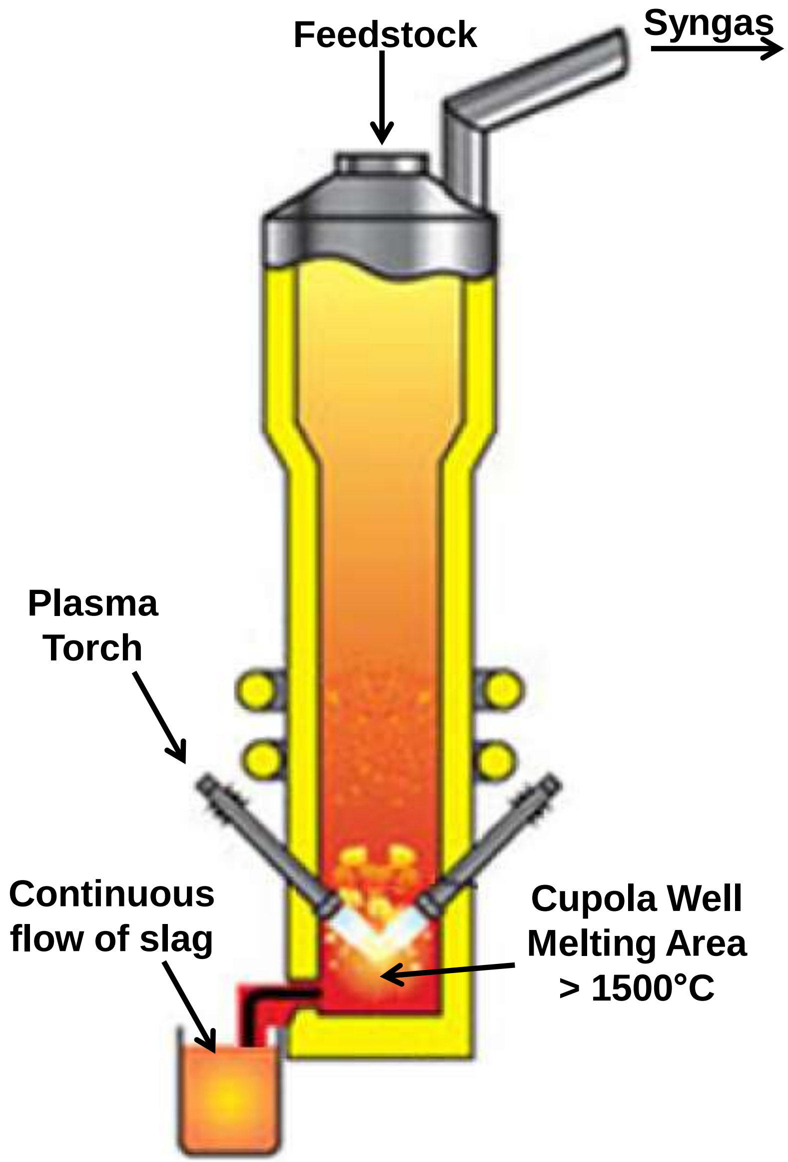
High Temperature Winkler Gasifier

- **Fluidized bed gasifier**
- **Dry feed**
- **Oxygen or air-blown**
- **Dry bottom ash**
- **Developed to utilize lignite coal**
- **Capable of gasifying broad range of feedstock**
- **Marketed for waste materials as Uhde PreCon process.**
- **Berrenrath demonstration plant**
  - In operation 1986 - 1997
  - 67,000 operating hours
  - 1.6 million tonnes dry lignite processed to produce 800,000 tonnes methanol



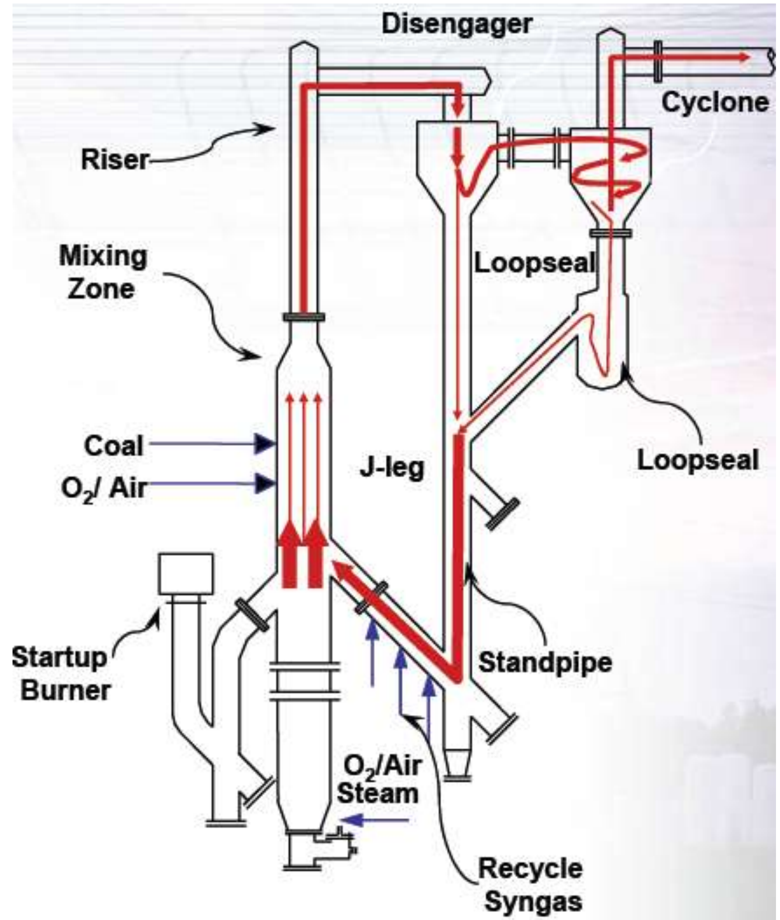
Alter NRG WPC Plasma Gasifier

- **Plasma gasification**
- **Atmospheric pressure**
- **Slagging**
- **Capable of gasifying broad range of feedstock**
- **Marketed for waste-to-energy and re-powering of solid-fuel power plants**
- **Relatively smaller gasifier**
- **2 projects in planning**
  - Retrofit of NRG Energy's 120-MW Somerset plant
    - Four 500 TPD gasifiers to be installed upstream of boilers
  - $2.5 M IGCC plant at former ERCO site, near Edmonton



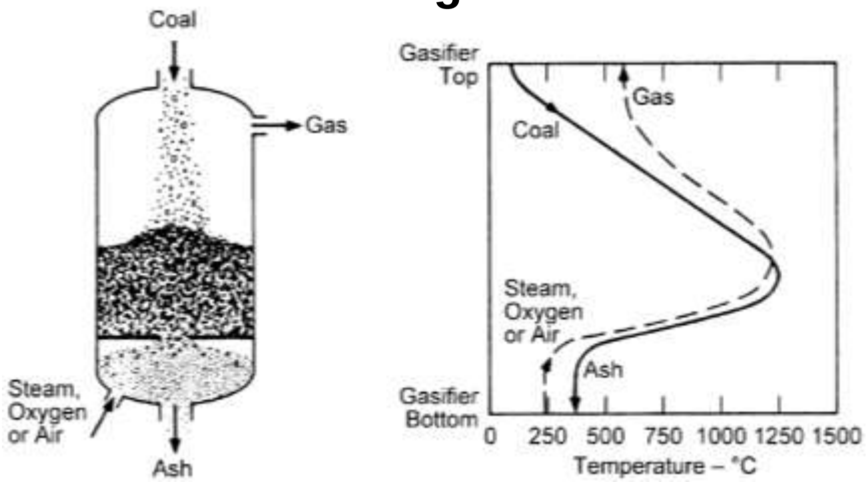
Kellogg Brown & Root (KBR) Gasifier
Transport Gasifier

- **Oxygen or air-blown**
  - Air blown for power generation
  - Oxygen for liquid fuels and chemicals
- **High reliability design**
  - Non-slagging
  - No burners
  - Coarse, dry coal feed
- **Planned 560 MWe IGCC with a 2x1 CC owned by Mississippi Power Company in Kemper County, MS**
  - June 2013 COD

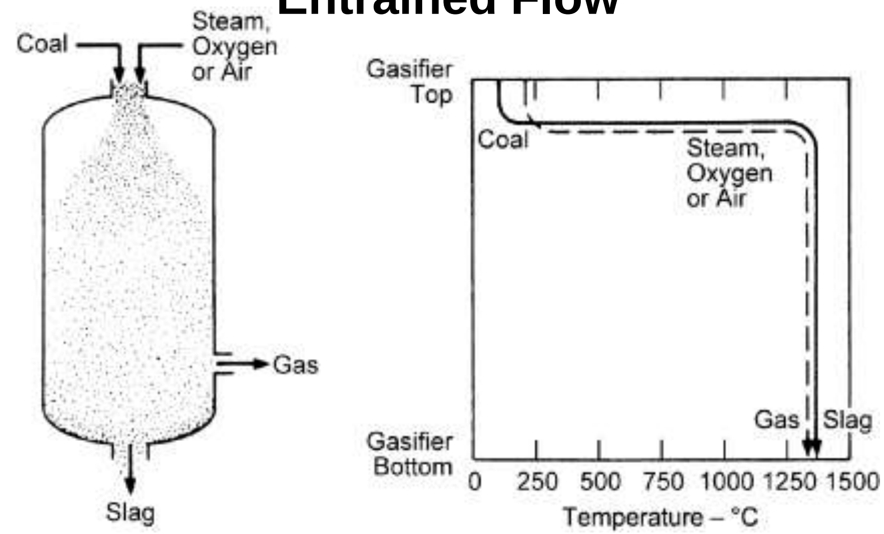


Gasifier Configurations

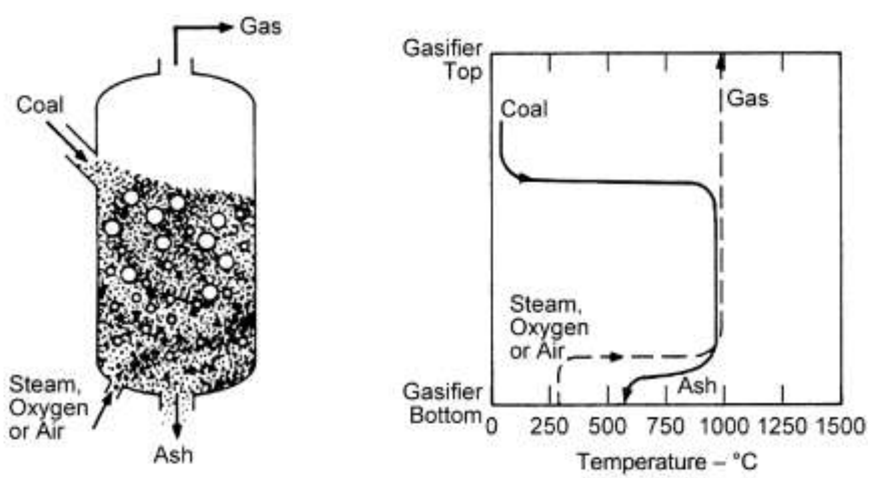
Moving Bed



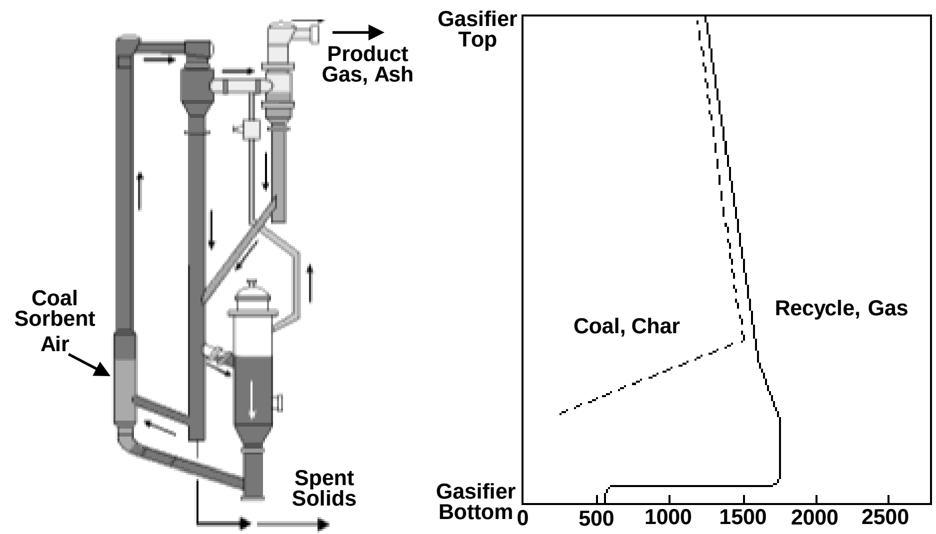
Entrained Flow



Fluidized Bed



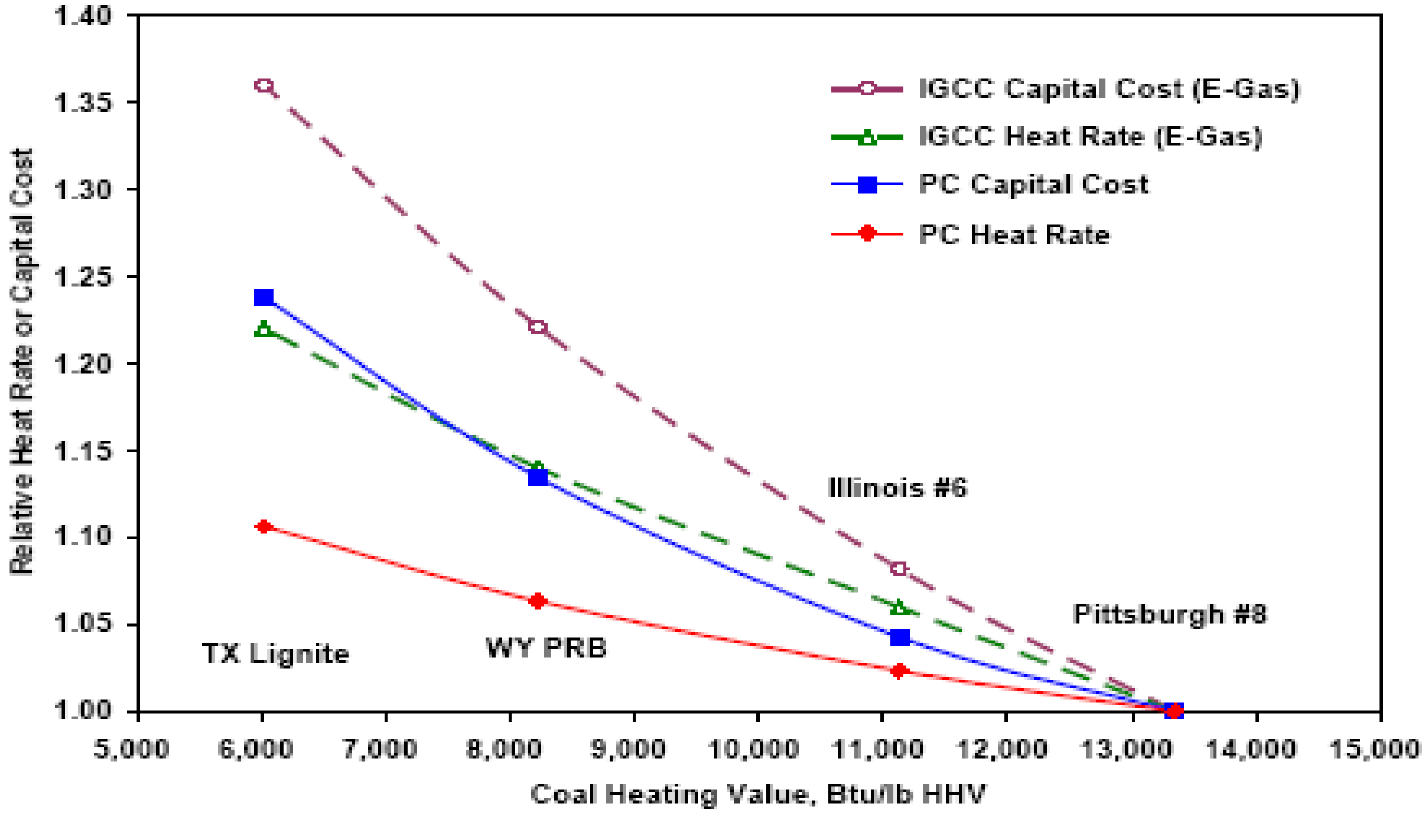
Transport



Comparison of Gasifier Characteristics

	Moving Bed		Fluidized Bed		Entrained Flow	Transport Flow
Ash Condition	Dry	Slagging	Dry	Agglomerate	Slagging	Dry
Coal Feed	~ 2 in	~ 2 in	~ 1/4 in	~ 1/4 in	~ 100 Mesh	~1/16in
Fines	Limited	Better than dry ash	Good	Better	Unlimited	Better
Coal Rank	Low	High	Low	Any	Any	Any
Gas Temp. (°F)	800-1,200	800-1,200	1,700-1,900	1,700-1,900	>2,300	1,500-1,900
Oxidant Req.	Low	Low	Moderate	Moderate	High	Moderate
Steam Req.	High	Low	Moderate	Moderate	Low	Moderate
Issues	Fines and hydrocarbon liquids		Carbon conversion		Raw gas cooling	Control carbon inventory and carryover

Effect of Coal Quality on PC and IGCC Plant Heat Rates and Capital Costs



Source: EPRI (Booras and Holt), "Pulverized Coal and IGCC Plant Cost and Performance Estimates", GTC Conference, October 2004

Polk

Wabash

Gasification
A Commercial Reality

Buggenum

Puertollano

Snapshot of IGCC Syngas Fuel Composition

& Typical Natural Gas Composition

Syngas	PSI	Tampa	El Dorado	Pernis	ILVA	Schwarze Pumpe	Sarlux	Fife	Exxon Singapore	Valero Delaware	[d]	Natural Gas
H_2	**24.8**	**37.2**	**35.4**	**34.4**	**8.6**	**61.9**	**22.7**	**34.4**	**44.5**	**32.0**	**33.4**	**trace**
CO	39.5	46.6	45.0	35.1	26.2	26.2	30.6	55.4	35.4	49.5	42.2	—
CH_4	1.5	0.1	0.0	0.3	8.2	6.9	0.2	5.1	0.5	0.1	0.1	93.9
CO_2	9.3	13.3	17.1	30.0	14.0	2.8	5.6	1.6	17.9	15.8	17.8	14.5
N_2 + Ar	2.3	2.5	2.1	0.2	42.5	1.8	1.1	3.1	1.4	2.2	5.7	48.2
H_2O	22.7	0.3	0.4	—	—	—	39.8	—	0.1	0.4	0.1	0.9
LHV[a]												
Btu/ft^3	209.0	253.0	242.0	210.0	183.0	317.0	163.0	319.0	241.0	248.0	230.4	134.6
kJ/M^3	8224.0	9962.0	9528.0	8274.0	7191.0	12492.0	6403.0	12568.0	9477.0	9768.0	9079.0	5304.0
GT Temperature												
°F	570.0	700.0	250.0	200.0	400.0	100.0	392.0	100.0	350.0	570.0	300.0	—
°C	330.0	371.0	121.0	96.0	204.0	38.0	200.0	38.0	177.0	299.0	149.0	—
H_2/CO ratio	0.63	0.80	0.79	0.98	0.33	2.36	0.74	0.62	1.26	0.65	0.79	0.46
Diluent	Steam	N_2	N_2/Steam	Steam	—	Steam	Moisture	H_2O	Steam	H_2O/N_2	N_2/H_2O	n/a
Equivalent LHV[b]												
Btu/ft^3	**150.0**	**118.0**	**113[c]**	**198.0**	—	**200.0**	—	[c]	**116.0**	**150.0**	**115.3**	**134.6**
kJ/M^3	5910.0	4649.0	4452.0	7801.0	—	7880.0	—	—	4660.0	5910.0	4543.0	5304.0

[a] Pre-diluent, [b] Post-diluent, [c] Always co-fired with 50% natural gas, [d] Confidential

Source: D. Todd GE - 2002

Commercial-Scale Coal IGCC Power Plants

U.S.

- Southern California Edison's 100 MWe Cool Water Coal Gasification Plant (1984-1988)
- Dow Chemical's 160 MWe Louisiana Gasification Technology Inc (LGTI) Project (1987-1995)
- PSI Energy's (now Cinergy) 262 MWe Wabash River Generating Station (1995 - present)
- Tampa Electric's 250 MWe Polk Power Station (1996-present)

International

- NUON/Demkolec's 253 MWe Buggenum Plant (1994-present)
- SUV 400 MWe Vresova Plant (1996-present)
- ELCOGAS 283 MWe Puertollano Plant (1998-present)
- Clean Coal Power 250 MWe Nakoso Plant (2007-present)

IGCC Plants in the U.S.

- **Southern California Edison's Cool Water Coal Gasification Plant**
  - 100 MWe – coal (1984-1988)
- **Dow Chemical's Louisiana Gasification Technology Inc (LGTI) Project**
  - 160 MWe – coal (1987-1995)
- **Wabash River Coal Gasification Repowering Project**
  - 262 MWe – coal/petcoke (1995 - present)
- **Tampa Electric Polk Power Station**
  - 250 MWe – coal/petcoke (1996 - present)
- **Valero Delaware City Refinery's Delaware Clean Energy Cogeneration Project**
  - 160 MWe & steam – petcoke (2002 – 2009)
- **Duke Energy's Edwardsport Integrated Gasification Combined Cycle Station**
  - 630 MWe – coal (2012 start up)

Coal/Petcoke-Based U.S. IGCC Plants

Operational Performance

	Cool Water California	LGTI Louisiana	Wabash River Indiana	Tampa Electric Florida	Valero Delaware
Net Power Output MWe	100	160	262	250	240
Efficiency, % (HHV basis)		37.5	40.2	37.5	
Gasification Technology	GE	E-Gas	E-Gas	GE	GE
Feedstock	Bituminous	Low sulfur subbituminous	Petcoke	Coal and petcoke blend	Petcoke
Gas Turbine	GE 107E	2 x Siemens SGT6-3000E	GE 7FA	GE 107FA	2 x GE 7FA
Firing Temp.,˚F (˚C) on natural gas*		2350 (1287)	2350 (1287)	2350 (1287)	
NO_x Control	Steam Dilution to Combustion Turbine	Steam Dilution to Combustion Turbine	Steam Dilution to Combustion Turbine	Nitrogen and Steam Dilution to Combustion Turbine	Nitrogen and Steam Dilution to Combustion Turbine

* *Syngas firing is usually 100-200˚F lower*

Worldwide Operating IGCC Projects

PROJECT- LOCATION	*DATE IN SERVICE*	*OUTPUT (MW)*	*FEEDSTOCK - PRODUCTS*
Nuon (Demkolec) - Buggenum, The Netherlands	1994	253	Coal/biomass - Power
PSI Wabash (Global/Cinergy) - Indiana USA	1995	262	Coal/petcoke - Power
Tampa Electric - Polk County, Florida USA	1996	250	Coal/petcoke - Power
SUAS - Vresova, Czech Republic	1996	400	Coal - Power & Steam
Shell Refinery - Pernis, The Netherlands	1997	120	Visbreaker tar - Power, H_2 & Steam
ELCOGAS - Puertollano, Spain	1998	320	Coal/petcoke - Power
ISAB Energy - Sicily, Italy	1999	510	Asphalt - Power
Sarlux/Enron - Sardinia, Italy	2000	550	Visbreaker tar - Power, H_2 & Steam
api Energia - Falconara, Italy	2001	250	Oil residue - Power & Steam
Exxon Chemical - Singapore	2002	180	Ethylene tar - Power
Nippon Petroleum (NPRC) - Negishi, Japan	2004	350	Asphalt - Power
ENI Sannazzaro - Italy	2006	250	Oil residue - Power
Institute for Clean Coal Technology - Yankuang, China	2006	72	Coal - Methanol & Power
Clean Coal Power - Nakoso, Japan	2007	250	Coal - Power
Nexen/Opti - Long Lake, Canada	2007	560	Asphaltene - Power, H_2 & Steam
Total Operating IGCC Output (MW)		*4577*	

IGCCs are using a variety of feedstocks

Based on: Gas Turbine World, Jan – Feb 2007

IGCC Technology in Early Commercialization
U.S. Coal-Fueled Plants

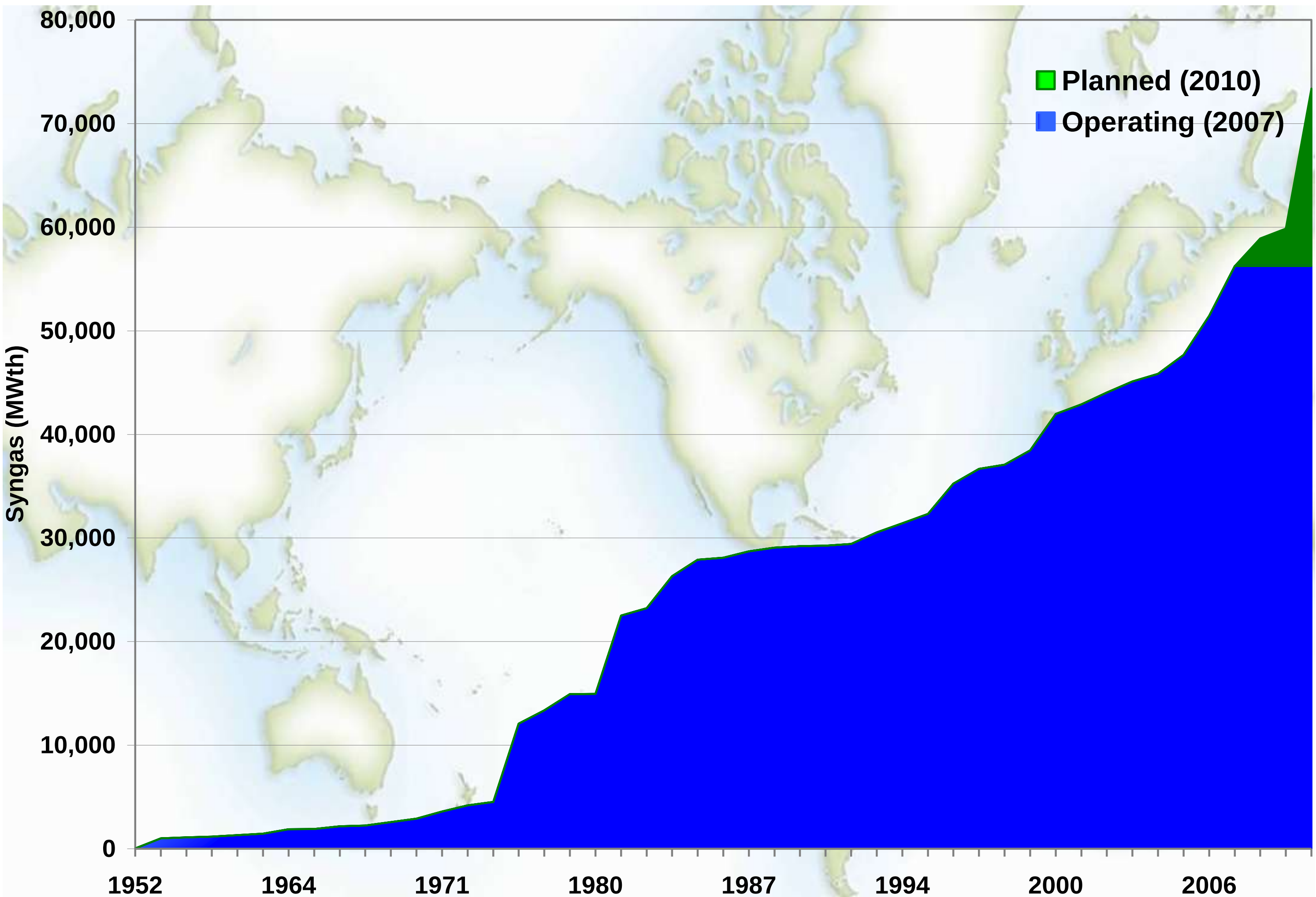
- **Wabash River**
  - 1996 Powerplant of the Year Award*
  - Achieved 77% availability **
- **Tampa Electric**
  - 1997 Powerplant of the Year Award*
  - First dispatch power generator
  - Achieved 90% availability **

Nation's first commercial-scale IGCC plants, each achieving
> 97% sulfur removal
$\geq$ 90% NOx reduction

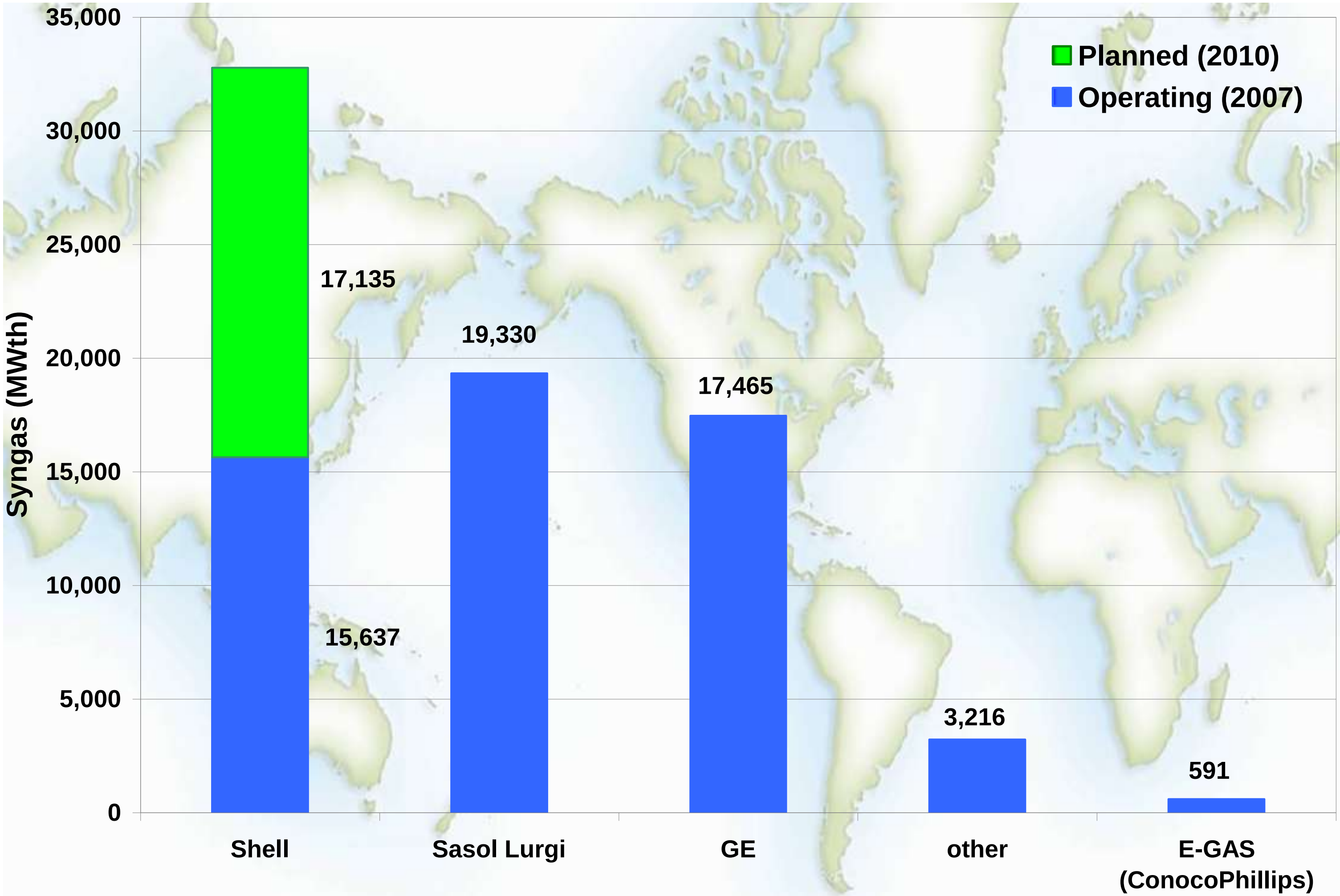
Power Magazine* * Gasification Power Block*

Worldwide Gasification Capacity and Planned Growth

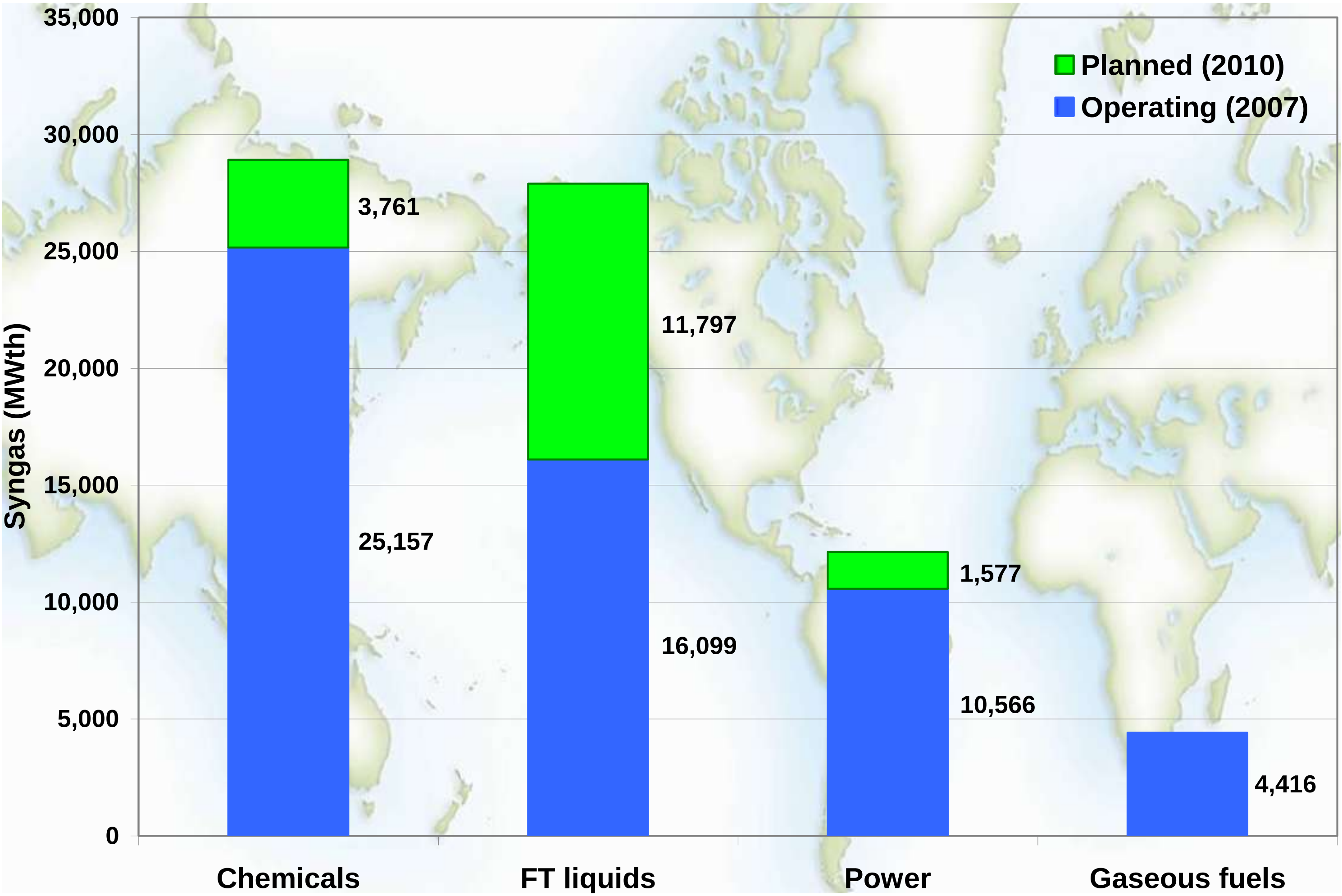
Cumulative by Year



Worldwide Gasification Capacity and Planned Growth
by Technology

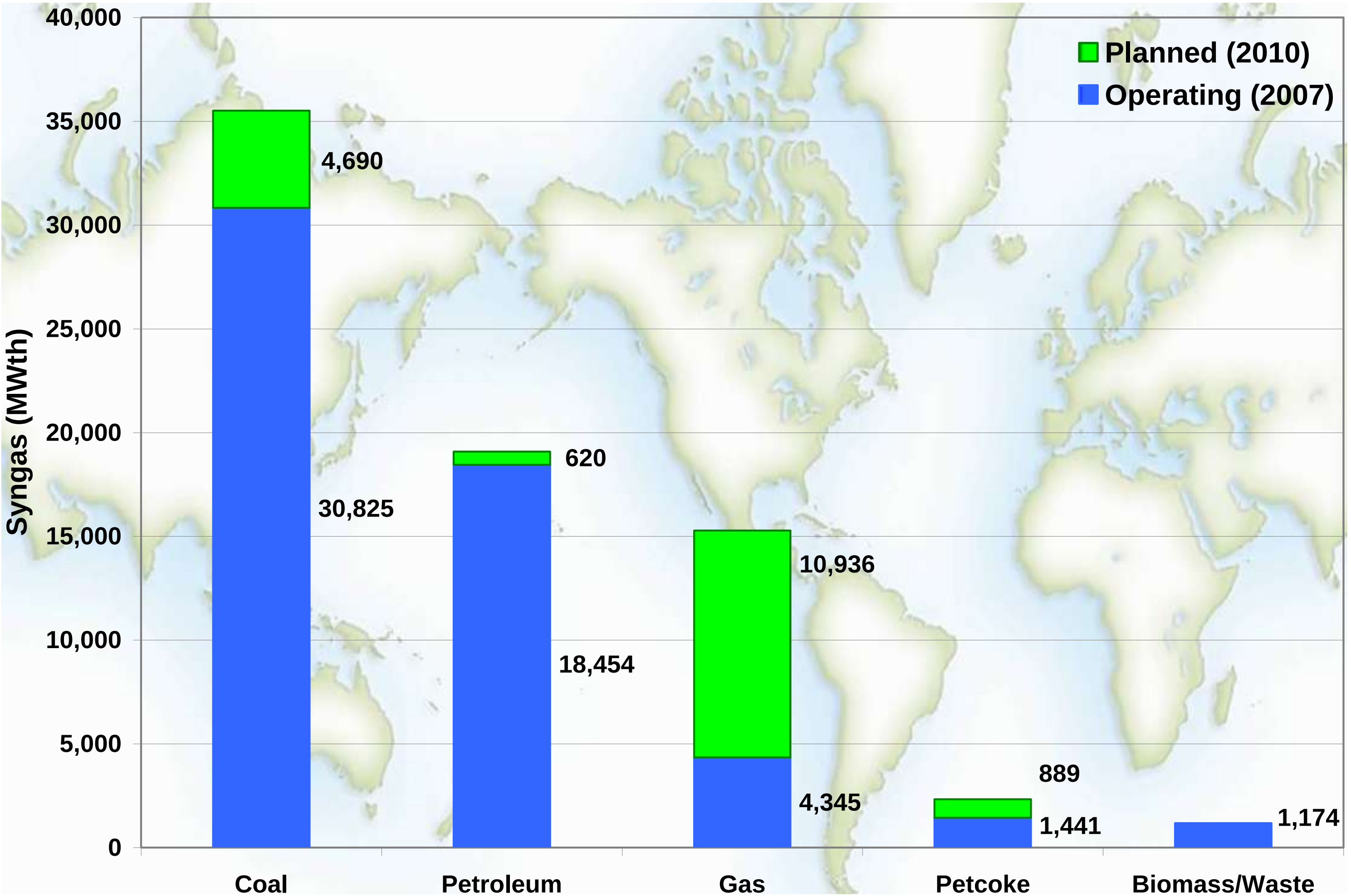


Worldwide Gasification Capacity and Planned Growth
by Product

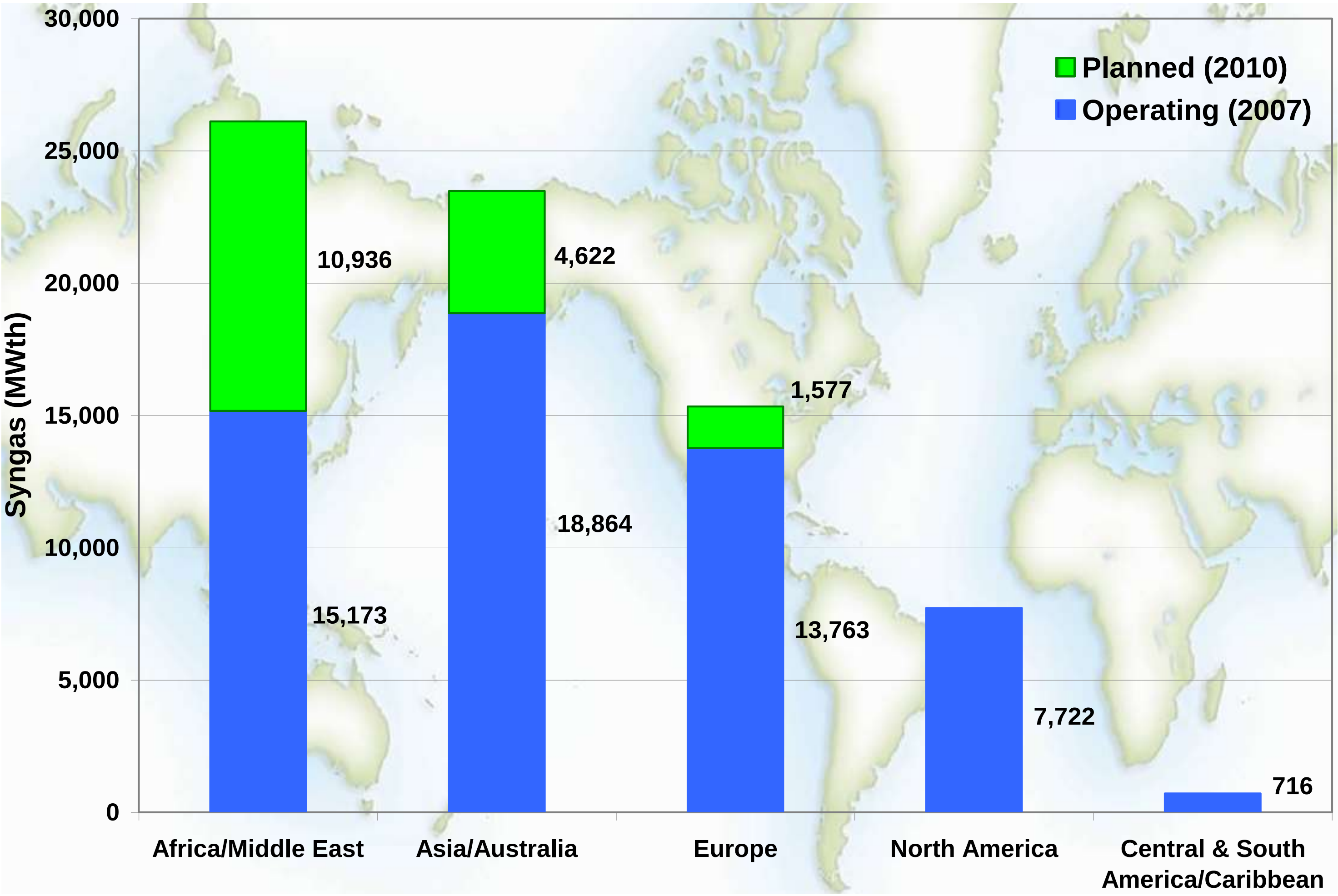


Worldwide Gasification Capacity and Planned Growth

by Primary Feedstock



Worldwide Gasification Capacity and Planned Growth
by Region



Survey Results

Operating Plant Statistics 2004 vs. 2007

2004

- **Operating Plants 117**
- **Gasifiers 385**
- **Capacity ~45,000 MWth**
- **Feeds**
  - Coal 49%
  - Petcoke 36%
- **Products**
  - Chemicals 37%
  - F-T 36%
  - Power 19%

2007

- **Operating Plants 144**
- **Gasifiers 427**
- **Capacity ~56,000 MWth**
- **Feeds**
  - Coal 55%
  - Petcoke 33%
- **Products**
  - Chemicals 45%
  - F-T 28%
  - Power 19%

Cool Water IGCC Demonstration Project
Daggett, California

- **First U.S. IGCC demonstration**
- **Operating period 1984-1989**
- **GE Technology (formerly Texaco, ChevronTexaco)**
- **Product gas fueled GE 7E combined cycle**
- **1,150 tons/day southern Utah (SUFCO) coal; 100 MWe Net**
- **Co-funded by Texaco, GE, EPRI & Southern California Edison**
- **Considerable information provided for development of full-scale plant**
- **Basis for Tampa Electric Polk Power Station**

Southern California Edison Site

Louisiana Gasification Technology Inc (LGTI) Project
Dow Chemical Plant — Plaquemine, Louisiana

- **Operating Period 1987-1993**
- **E-Gas ConocoPhillips**
  - formerly Dow, Dynergy
- **2,400 TPD Powder River Basin (PRB) Coal; 160 MWe**
- **Product gas fueled two Westinghouse modified W501D5 gas turbines**
  - 80% syngas
  - 20% natural gas
- **85,000 hours on syngas**
- **160 MWe Net**

http://www.gasification.org/Docs/Penwell%202005/PowerGen%202005_Amick_r1.pdf

Valero Refinery
Delaware City, Delaware

- **Operating Period 2002-2009**
- **2 GE gasifiers**
  - formerly Texaco
- **Oxygen blown**
- **2 Combustion turbines**
  - GE 6FA
- **2,100 tons/day feedstock**
  - petcoke
- **Plant startup July 2002**
- **Power generation**
  - Combustion turbines: 180 MWe
  - Steam turbine: 60 MWe
  - **Net output: 240 MWe**

Gasification Facility at Delaware City Refinery

Wabash River Generating Station

SG Solutions – West Terre Haute, Indiana

- **Plant startup July 1995**
- **E-Gas gasifier**
  - ConocoPhillips
- **2,500 tons/day coal or petcoke**
- **Bituminous coal**
  - 1995 thru August 2000
- **Petcoke**
  - 2000 thru Present
- **DOE CCT Round IV**
  - Repowering project

- **Power generation**
  - Combustion turbine: 192 MWe
  - Steam turbine: 105 MWe
  - Internal load: -35 MWe
  - Net output: **262 MWe**

Wabash River IGCC Plant Aerial Photo

Polk Power Station Unit 1,
Tampa Electric Co. – Mulberry, FL

- **GE Gasifier**
  - oxygen blown
  - slurry fed
  - entrained flow
- **Vessel refractory lined**
  - largest built
- **Feedstock 2,200 tons/day**
  - coal and petcoke blend
- **CT is GE 7F**
- **Single train configuration**
  - one gasifier supplying one CT
- **Acid gas removal via**
  - MDEA and COS hydrolysis
- **DOE Clean Coal Technology Program**
  - Plant startup July 1996

- **Power generation**

– Combustion turbine:	192 MWe
– Steam turbine:	123 MWe
– Internal load:	- 55 MWe
– Other auxiliaries:	- 10 MWe
– **Net output**	**250 MWe**

Courtesy: Tampa Electric Co.

Polk Power Station Aerial Photo

ELCOGAS

Puertollano, Spain

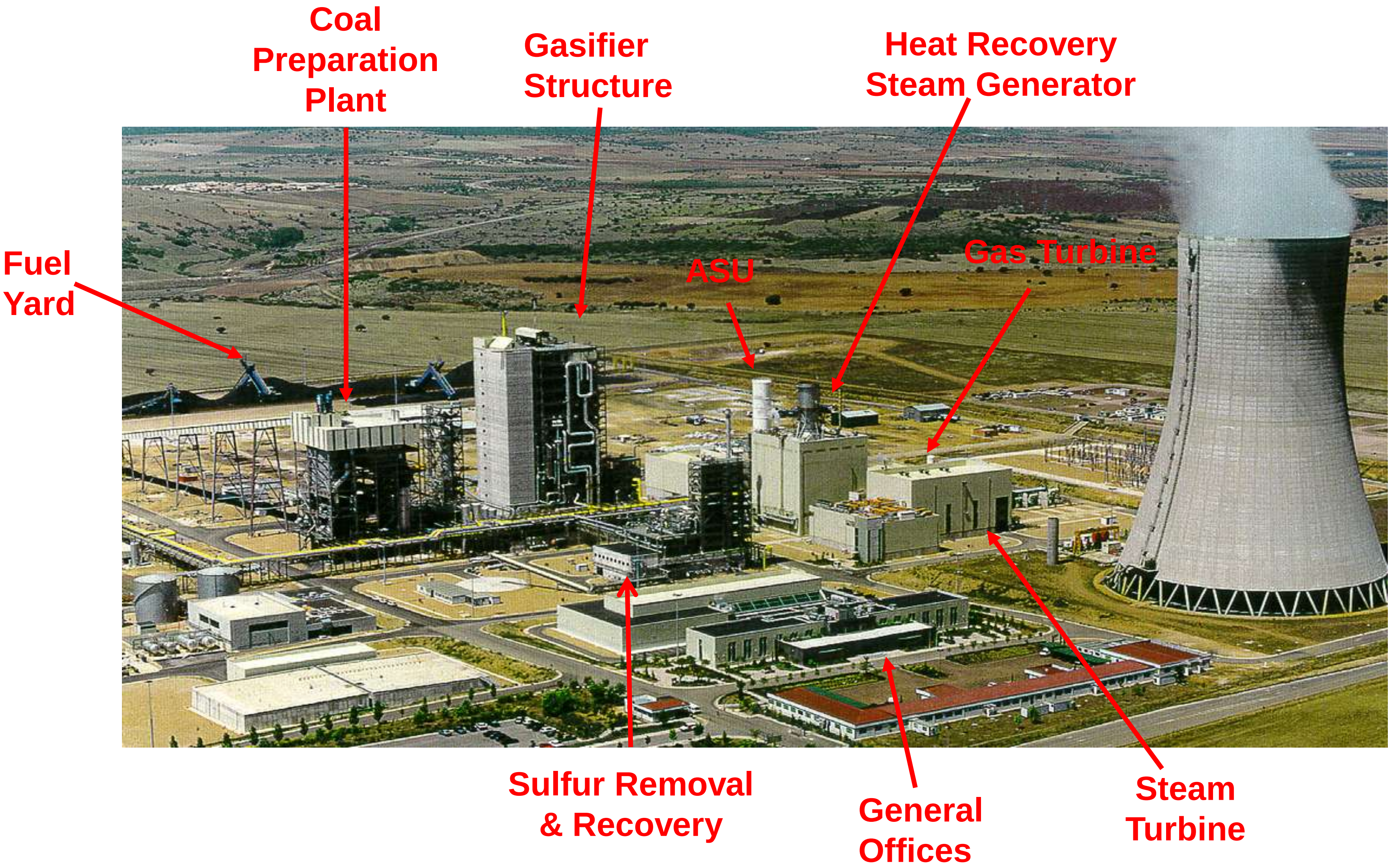
- **PRENFLO gasifier**
  - Pressurized entrained flow gasifier now offered by Uhde
- **Oxygen blown**
- **2,600 tons/day coal and petcoke**
- **Commercial operation began in 1996 w/ natural gas**
- **In 1998 began operating on 50/50 Petroleum coke / local Spanish coal (~ 40% ash)**
- **Siemens V94.3 gas turbine**
- **Independent power project without a power purchase agreement (PPA).**

IGCC Plant Puertollano, Spain

Power generation	ISO	at site
– Combustion turbine:	200 MW	182.3 MWe
– Steam turbine:		135.4 MWe
– Internal load:	______	- 35.0 MWe
– **Net output:**	300 MW	282.7 MWe

Source: "Integrated gasification combined cycle technology: IGCC – Its actual application in Spain: ELCOGAS, Puertollanl" Manuel Treviño Coca
Image Source: www.elcogas.es/shared/enter_img2_r1_c1.jpg

ELCOGAS Plant Aerial Photo



Gasworks of Sokolovská uhelná, a.s. (SUAS)

Vřesová, Czech Republic

- **26 Lurgi Gasifiers**
  - Entrained flow
  - Dry coal feed
- **Feedstock**
  - Lignite
- **2 Combustion turbines**
  - FRAME 9 E (9171 E) licensed by GE
- **Steam turbine**
  - (PP 60 – 71) supplied by ABB ES
- **Plant startup**
  - 1996 converted to IGCC
  - 1970 town gas

Vřesová IGCC Plant, Czech Republic

- **Power generation**
  - Combustion turbine: 309 MWe
  - Steam turbine: 114 MWe
  - Internal load: - 25 MWe
  - **Net output: 398 MWe**

http://www.gasification.org/Docs/2005_Papers/05CHHO.pdf

Autothermal Oil Conversion Plant

Sokolovská uhelná, a.s. Vřesová, Czech Republic

- **Siemens SFG-200**
  - Entrained flow
  - Oxygen blown
  - Refractory lined
  - 175 MWth (28 bar)
  - Full quench
- **Feedstock**
  - Carbon chemical products (i.e., phenols, tars, and petrol), created during gasification of lignite in 26 Lurgi generators
- **Plant startup**
  - June 2007

Installation of Siemens Gasifier Gasworks of Sokolovská uhelná

http://www.gasification.org/Docs/News/2007/COALGEN/Siemens%20COALGEN%2007.pdf

SUAS Aerial Photo

Nuon IGCC Plant
Buggenum, The Netherlands

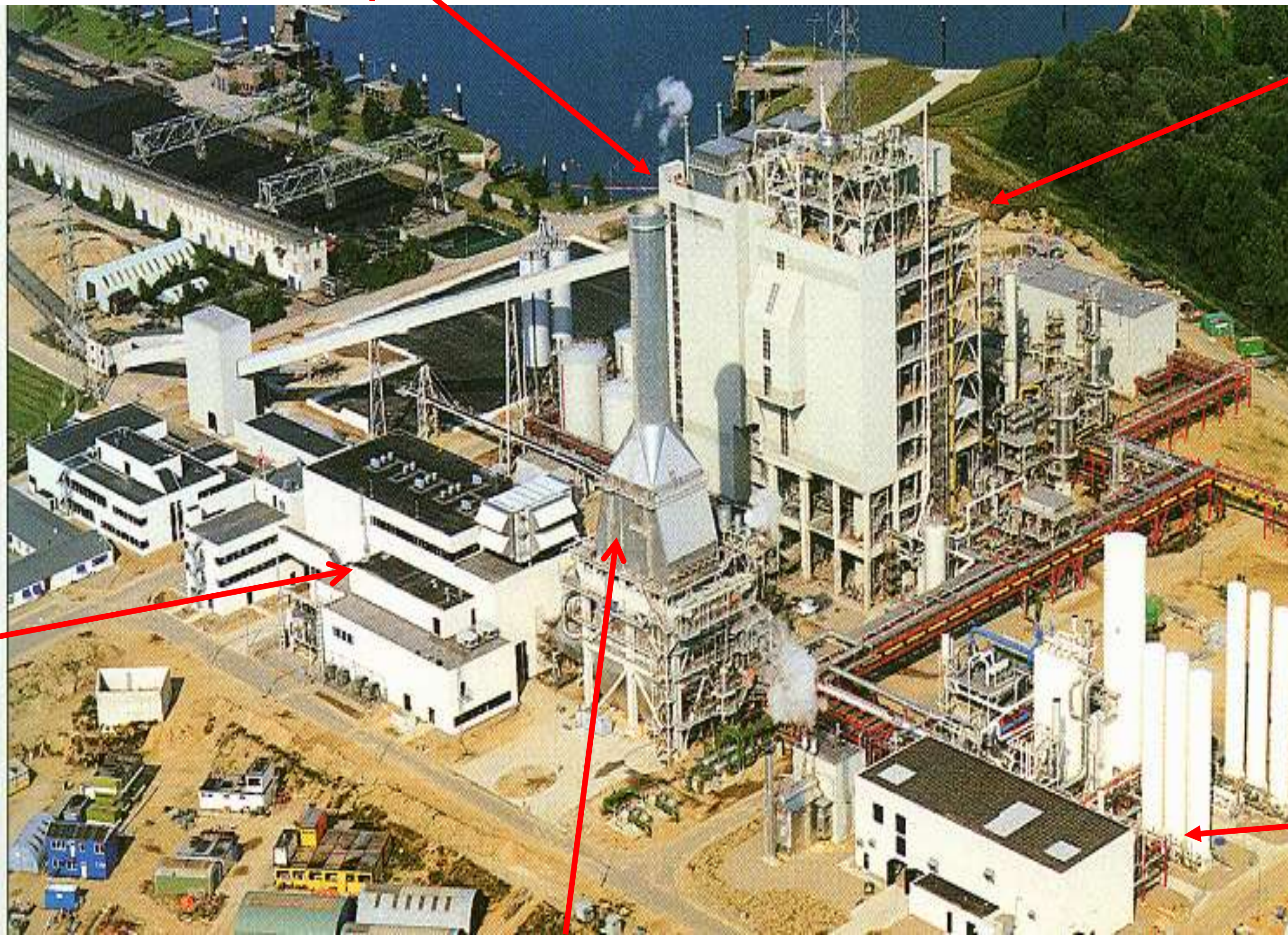
- **Shell Gasification**
  - offered jointly with Krupp Uhde
- **Gas turbine: Siemens V94.2**
- **2,000 tons/day feedstock**
  - bituminous coal
  - biomass
- **Plant startup 1993**
- ***Only large-scale biomass installation in operation today***

Buggenum IGCC Plant

- **Power generation**
  - Combustion turbine: 155 MWe
  - Steam turbine: 128 MWe
  - Internal load: - 30 MWe
  - **Net output: 253 MWe**

http://www.gasification.org/Docs/2005_Papers/05CHHO.pdf

Nuon Plant Aerial Photo



Note: Sulfur Removal & Recovery (out of view)

Courtesy: Nuon *SL/Rt 05.10.99*

Clean Coal Power R&D IGCC Demonstration Plant

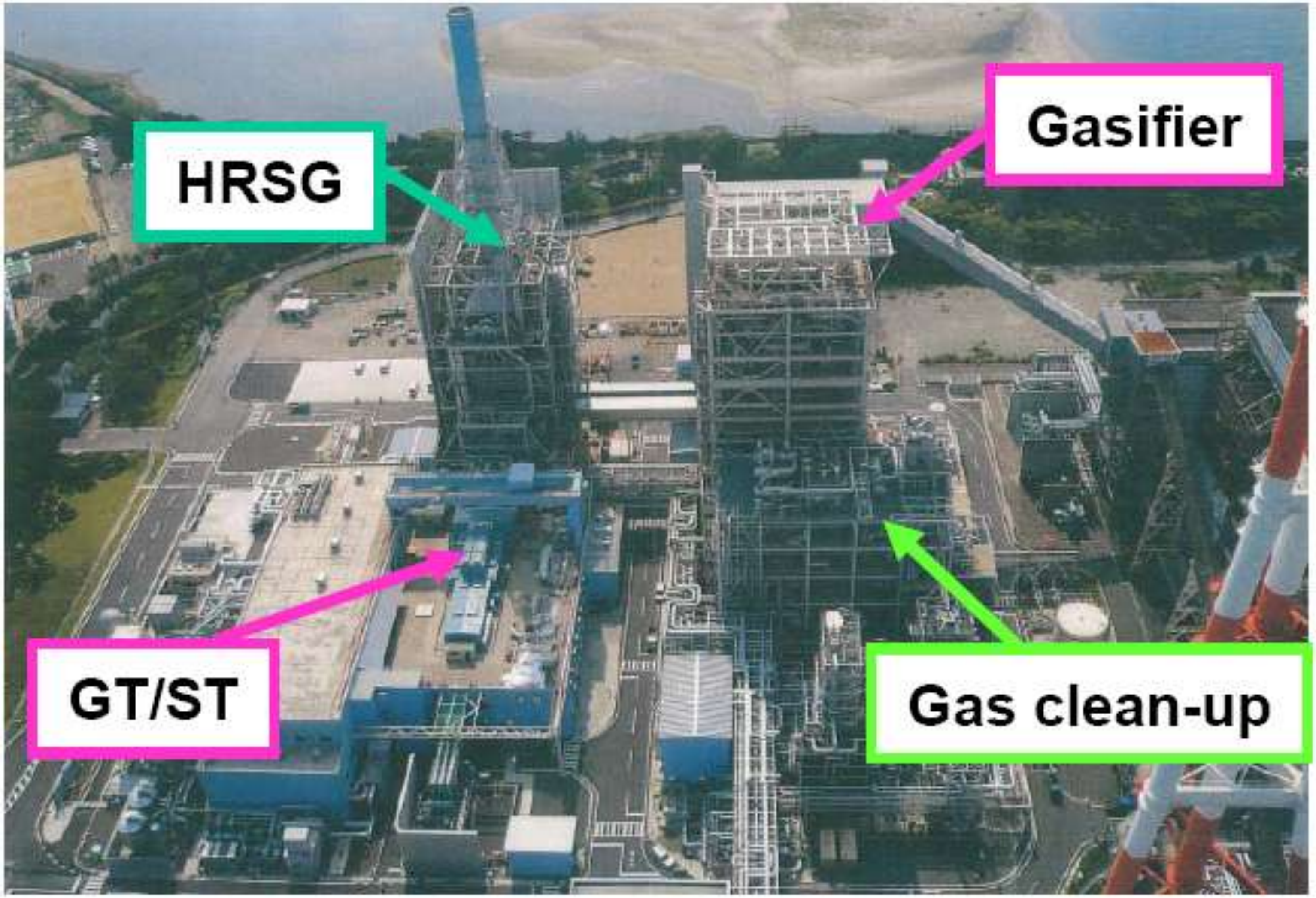
Nakoso, Japan

- **Mitsubishi Gasifier**
  - 250 MWe
  - Air-blown
  - Entrained flow
  - Dry coal feed
- **1,700 tons/day coal**
  - Suited to wide range of coals
- **Water wall structure**
- **Gas clean-up MDEA chemical absorption**
- **Plant startup**
  - September 2007

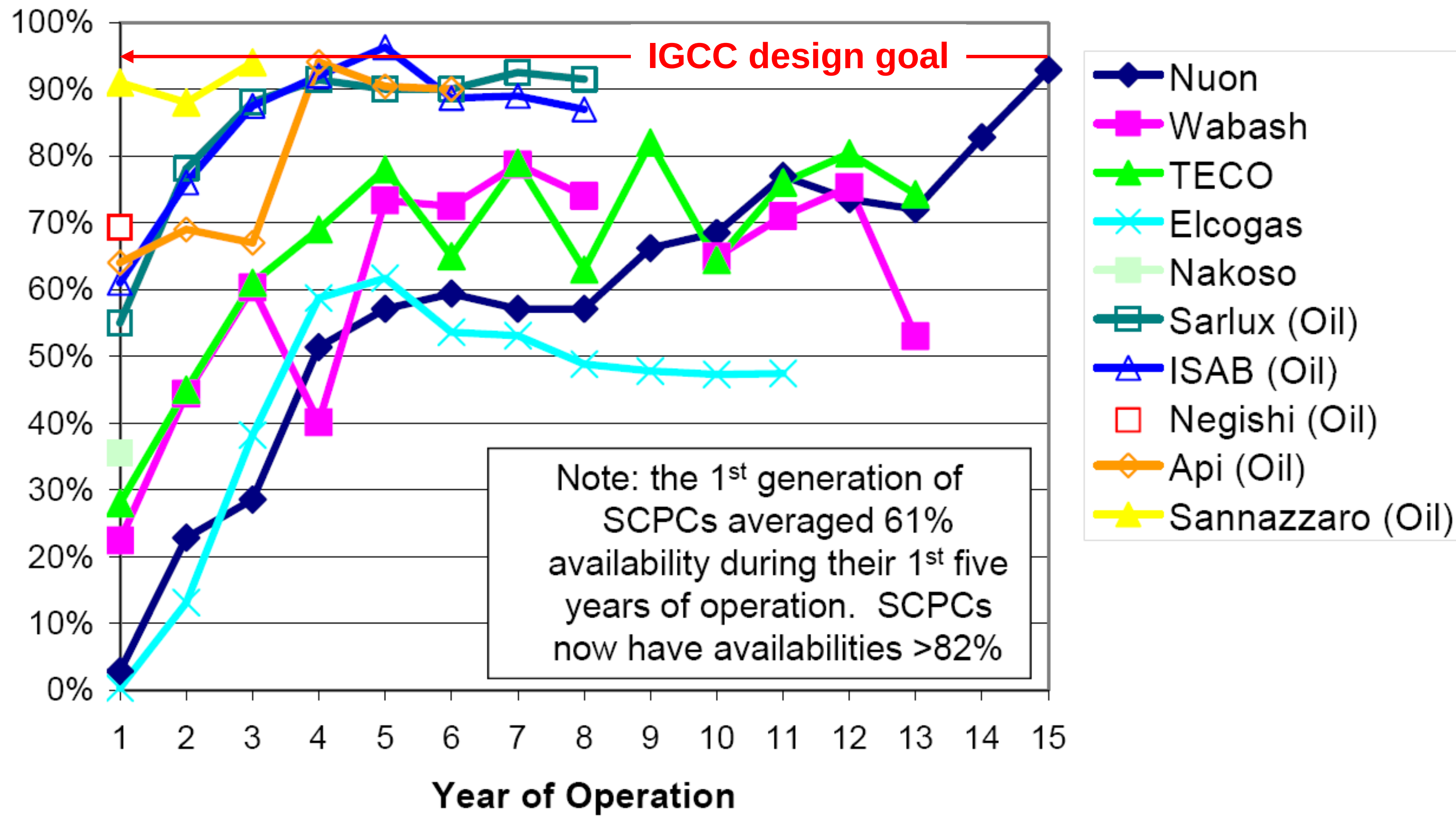
- **Clean Coal Power R&D *joint project of:***
  - Mitsubishi Heavy Industries,
  - Ministry of Economy, Trade and Industry, and
  - Several EPC companies

Clean Coal Power R&D IGCC Demonstration Plant

Aerial Photo



IGCC Availability History



Excludes impact of operation on back-up fuel

*Source: **Dr. Jeff Phillips** Sr. Program Manager, Advanced Coal, EPRI*
http://www.gasification.org/Docs/Workshops/2009/Kingsport/01Phillips.pdf

Dakota Gasification Company - SNG

Beulah, North Dakota

- **Part of Basin Electric Power Cooperative**
- **Plant startup 1984**
- **Coal consumption exceeds 6 million tons/year**
- **Produces more than 54 billion standard cubic feet of SNG per year**
  - also produces fertilizers, solvents, phenol, carbon dioxide, and other chemical
- **200 mmscfd CO_2 capacity**
- **EnCana injecting 7,000 tonnes/day**
  - increasing oil production by 18,000 barrels/day
- **Apache injecting 1,800 tonnes/day**

Great Plains Synfuels Plant

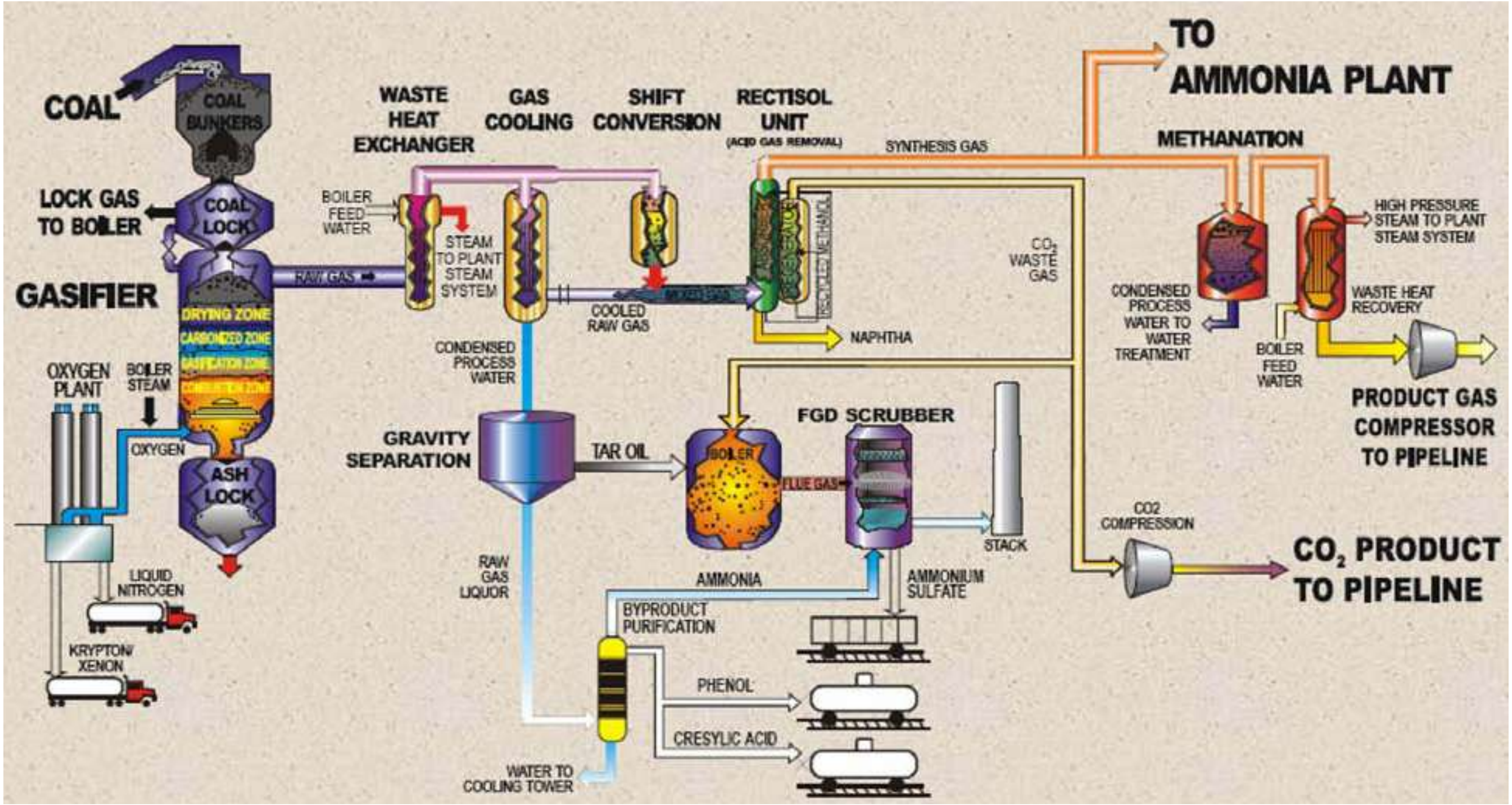
CO_2 is captured, pressurized, and piped 205 miles to Saskatchewan and sold for use in enhanced oil recovery (EOR) by EnCana and Apache Canada

Great Plains Synfuels Plant

Aerial Photo

Dakota Gasification

Process Schematic



Eastman Chemical Company

Kingsport, Tennessee

- **"Coal-to-Chemicals" Facility**
- **Plant startup 1983**
- **Texaco gasifiers**
- **Gasifies 1,200 tons/day Central Appalachian medium sulfur coal**
- **Sulfur compounds and ash are removed from the syngas**
- **Syngas is used to make methanol, acetic acid, acetic anhydride, methyl acetate…**

Courtesy: Eastman Chemical Co.

Eastman Chemical Company
Kingsport, Tennessee

SASOL I

Sasolburg, South Africa

- **Plant startup in 1955**
  - 17 Sasol-Lurgi Fixed Bed Dry Bottom (FBDB) gasifiers
  - 100% Sub-bituminous coal feedstock
  - Fisher-Tropsch process for Liquid Chemicals production
- **Supplies syngas to**
  - Sasol Wax to produce
    - Fischer-Tropsch hard waxes
  - Sasol Solvents to produce
    - methanol and butanol
  - Sasol Nitro to produce
    - ammonia

- ***2004 plant converted from coal gasification to natural gas reforming***
  - *Gasifiers decommissioned 2005*
  - *Replaced with 2 natural gas autothermal reformers*

Photo: John Sichinga

SASOL II & III

Secunda, South Africa

- **Plant startup in 1974**
- ***80* Sasol-Lurgi Fixed Bed Dry Bottom (FBDB) gasifiers**
- **155,000 bl/d production levels achieved in 2004**
- **Sub-bituminous coal feedstock, supplemented with natural gas**
- **Fisher-Tropsch process for Liquid Fuels & Chemicals production**

Photo: Courtesy Sasol

Coffeyville Resources Nitrogen Fertilizers

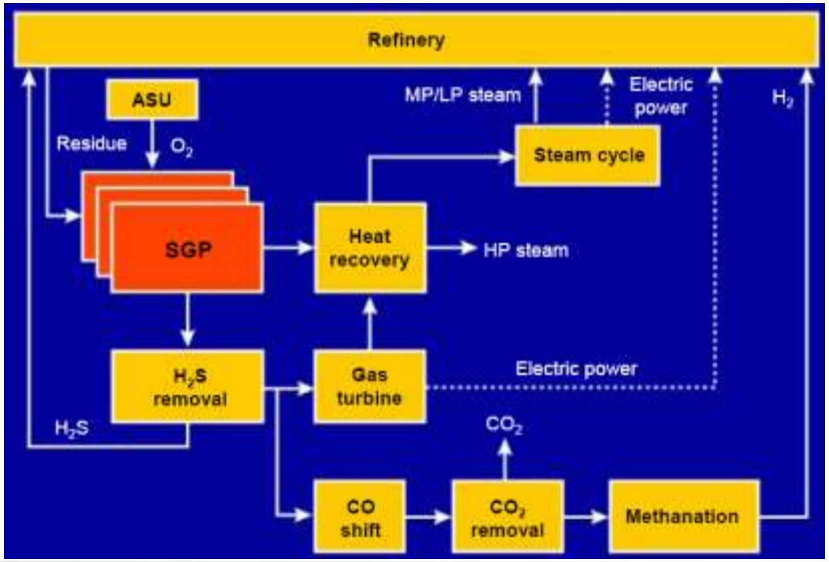
Coffeyville, Kansas

- **Plant converted from natural gas to petcoke to reduce costs by adding GE Energy gasifier**
- **Produces syngas with CO and H_2**
- **Syngas shifted to CO_2 and H_2**
- **CO_2 removed, leaving concentrated H_2 stream**
- **H_2 used to make ammonia for fertilizer**
- **326,663 short tons ammonia in 2007**

Technology suitable for Carbon Capture

Pernis Refinery IGCC/Hydrogen Project

- Major $2.2 billion refinery renovation
- Completed May 1997
- Gasifies 1,656 mt/d visbreaker residue
- Produces 118 MMscf/d H_2
- 3 Shell Gasifiers
- Rectisol process for gas cleanup
- 2 General Electric 6B turbines



Edwardsport IGCC Project

Rendering of the proposed IGCC power plant located at Duke Energy's Edwardsport Station near Vincennes, Indiana

- GE Gasifier
- 630 MWe
- 1.5 million tons of coal per year
- Operational - 2012
- Total project cost:
  - $2.5 billion
  - $133.5 million Federal investment tax credit award
  - $460 million in local, state and federal tax incentives
- Located:
  - Knox County, Indiana

Environmental Benefits

Air Permitting

IGCC and Gasification Plants

- Emission controls for IGCC and gasification
- Applicable regulations for IGCC
- Comparing IGCC with PC and NGCC
- New Source Performance Standards
- IGCC emission rate comparison
- Startup and shutdown emissions

IGCC New Source Performance Standards (NSPS)

Emission	*NSPS*	*NSPS on Gasifier Input Basis (calculated)*
NO_x	1.0 lb/MWh*	0.143 lb/MMBtu
SO_2	1.4 lb/MWh* and minimum 95% removal	0.2 lb/MMBtu
Particulate Matter	Lesser of 0.14 lb/MWh* or 0.015 lb/MMBtu**	0.011 lb/MMBtu
Mercury (bituminous coal)	20×10^{-6} lb/MWh*	2.87 lb/TBtu

* Output-based standards are on a gross generation basis
** Gas turbine heat input basis, filterable PM only

Steve Jenkins 2007 GTC Conference http://www.gasification.org/Docs/2007_Papers/22JENK.pdf

Emission Rate Units

- **IGCC permits list emission rates as lb/MMBtu of:**
  - Gasifier (coal) heat input, or
  - Gas turbine heat input basis
- **EPA's comments on the new NSPS addressed this:**

  "The heat input for an IGCC facility is the heat content of the syngas burned in the stationary combustion turbine and not the heat content of the coal fed to the gasification facility. The gasification facility is not part of the affected source under subpart Da, only the stationary combustion turbine are covered."
- **Emission rates are to be expressed on basis of:**
  - Syngas input to the gas turbine
- **Permit applications or permits can list "equivalents"**
  - on gasifier input basis, and
  - lb/hr and ppm

Important to specify heat input basis in permit application

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Potential Feedstocks

- **IGCC isn't necessarily "coal" gasification, other feedstocks could include:**
  - Petroleum coke
  - Biomass
  - Blends of the above

All Potential Feedstocks Should Be Included in Permit Application

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Air Emissions

- **Unique emission points depend on technology provider, may include:**
  - Flare
  - Sulfur recovery unit tail gas incinerator
  - Sulfuric acid plant stack
  - Tank vent incinerators
  - Air separation unit cooling tower



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Air Permitting

- **For air permit application:**
  - Preliminary engineering required to provide sufficient information for permit application
  - Emission inventory has to be developed
  - Startup, shutdown and emergency emissions must be calculated for ambient air quality modeling
  - Emissions from flare must be determined
    - Raw syngas
    - Clean syngas
    - Duration
    - Number of flare events per year

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What About SCR for IGCC?

- **Technical issues**
  - The <u>fuel</u> is syngas, not natural gas as in NGCC
  - Ammonium sulfate/bisulfate deposit in the HRSG, causing corrosion and plugging, requiring numerous washdowns
  - No <u>coal-based</u> IGCC system in the world uses SCR
- **Economic Issues**
  - No commercial guarantees yet with syngas
  - Deep sulfur removal, i.e. Selexol, is required, with higher capital cost

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Use of SCR on IGCC Plants

- **SCR has been *proposed* on some units:**
  - As BACT for NO_x
  - As an Innovative Control Technology to reduce emissions beyond diluent injection
  - As a trial/experiment, with emission limits only for natural gas use
  - To evaluate SCR with a syngas-fired combined cycle unit
  - To minimize NO_x emissions in order to reduce costs for NO_x allowances

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Use of SCR on IGCC Plants cont.

- **EPA addressed SCR in 2006 report**
- **Noted technical problems with using SCR on IGCC plant**
  - Noted SCR issues with IGCC plants using liquid feedstocks
  - Evaluated SCR with Selexol for deep sulfur removal


EPA

Final Report

Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies

- **Concluded that:**
  - Even with Selexol, SCR problems are not solved
  - Additional cost and reduced output are negative impacts to IGCC
  - BACT will continue to be a case by case issue

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Air Emission Rate Comparisons

- **NO_x and SO_x data is from publicly available information:**
  - Permit applications
  - Draft permits
  - Final permits
  - Submittals to other agencies
- **Data provided on gasifier and gas turbine heat input basis**
  - Calculated when not provided in data sources

IGCC plants included in charts:

- **AEP Mountaineer**
  - Permit application
- **Duke Energy Indiana Edwardsport**
  - Permit application
- **Energy Northwest Pacific Mountain Energy Center**
  - Permit application
- **ERORA Taylorville Energy Center**
  - Final permit
- **Excelsior Energy Mesaba**
  - Permit application
- **Orlando Gasification**
  - Final permit
- **Tampa Electric Company Polk Unit #6**
  - Permit application

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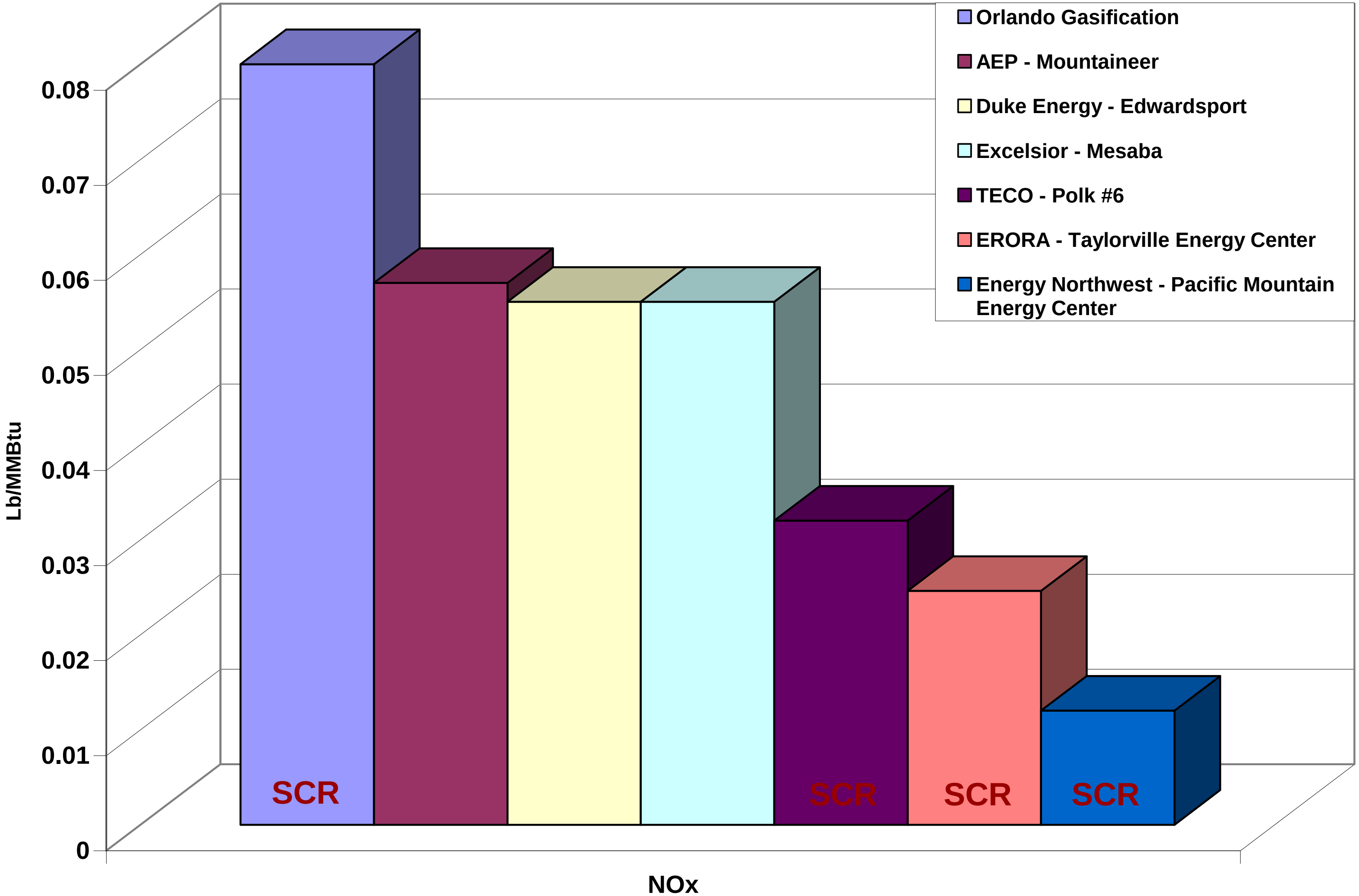
NOx Emission Rate Comparisons

Gasifier Heat Input Basis



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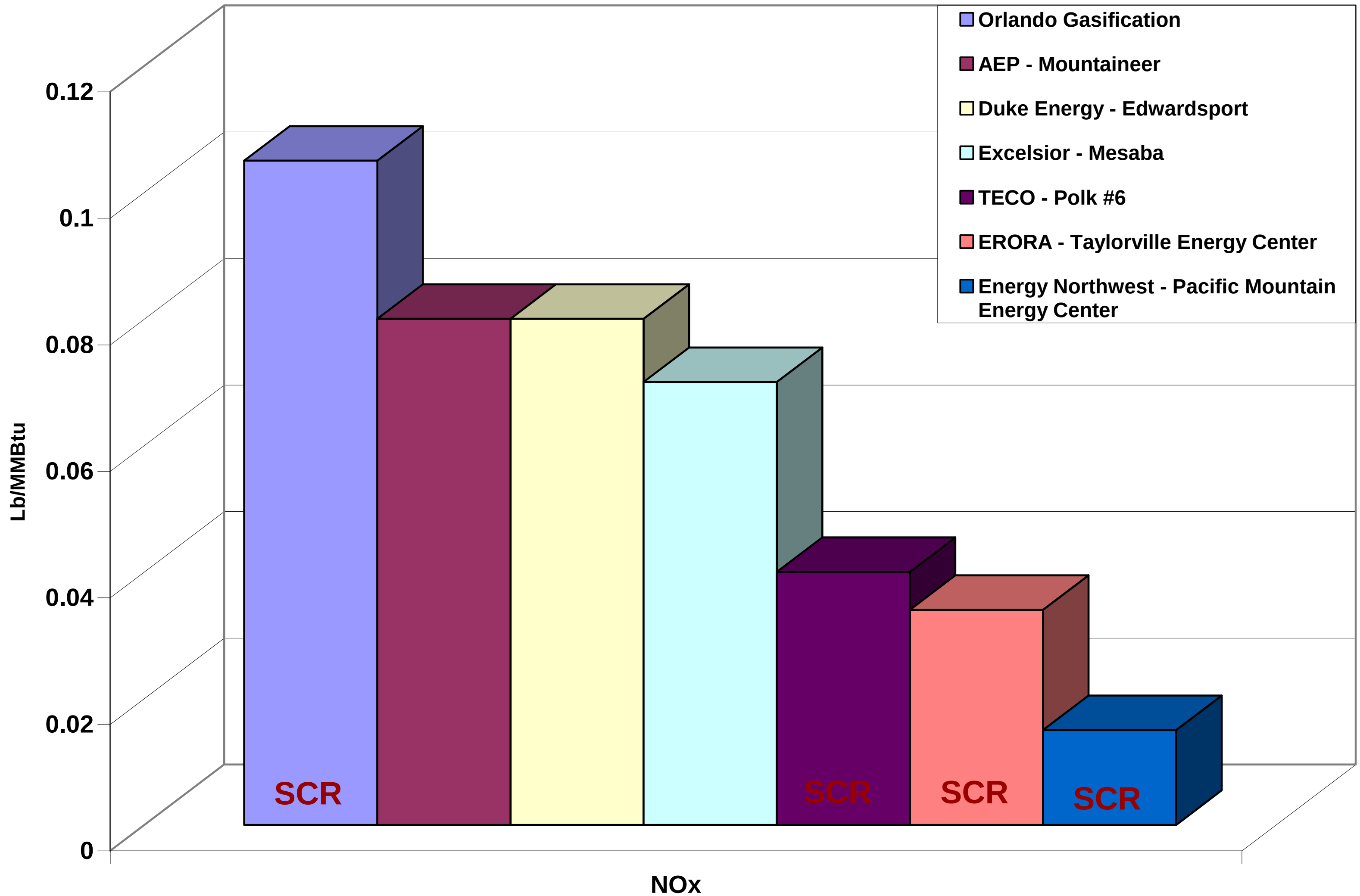
NOx Emission Rate Comparisons
Gas Turbine Heat Input Basis



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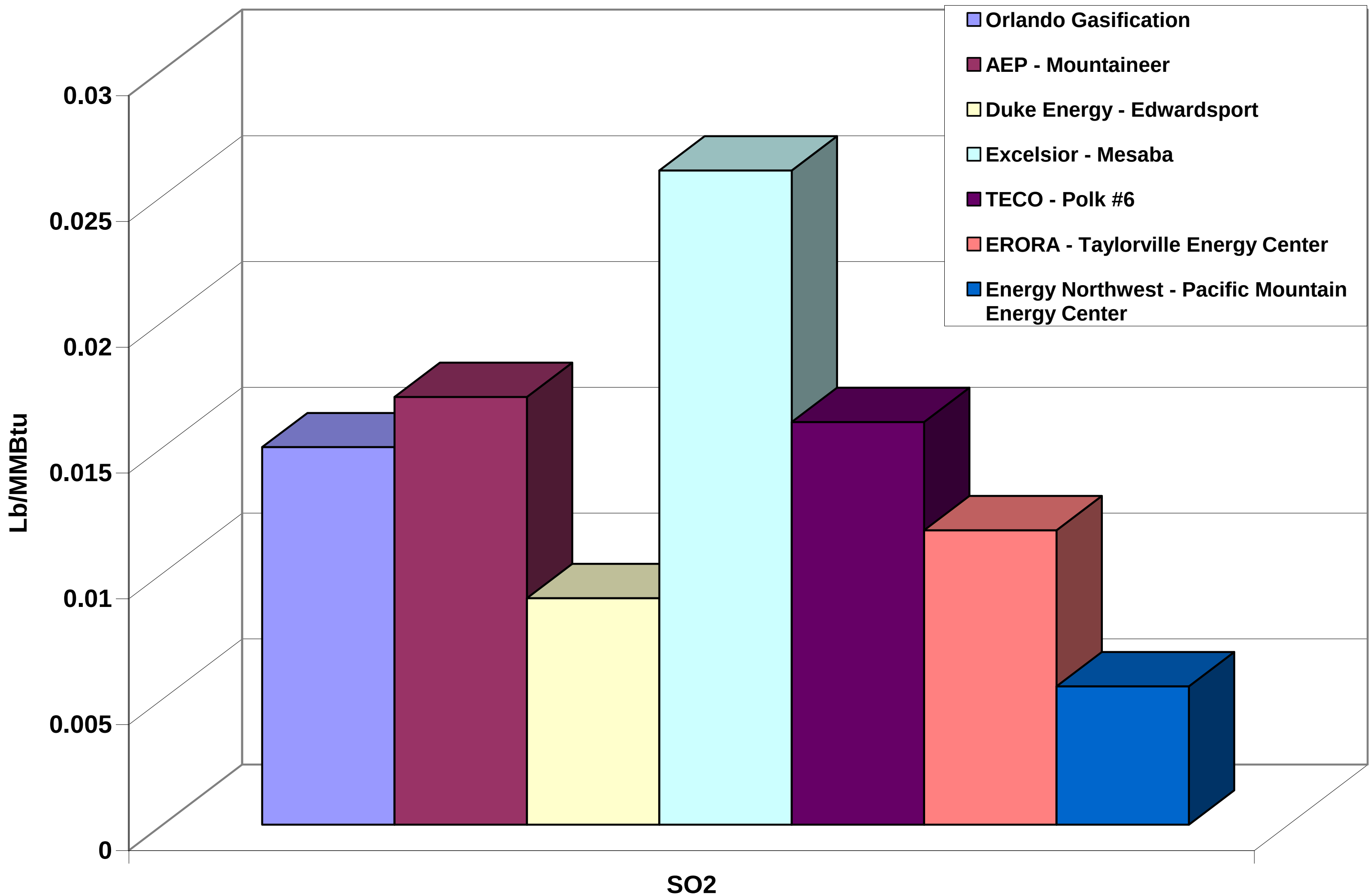
SO_2 Emission Rate Comparisons

Gasifier Heat Input Basis



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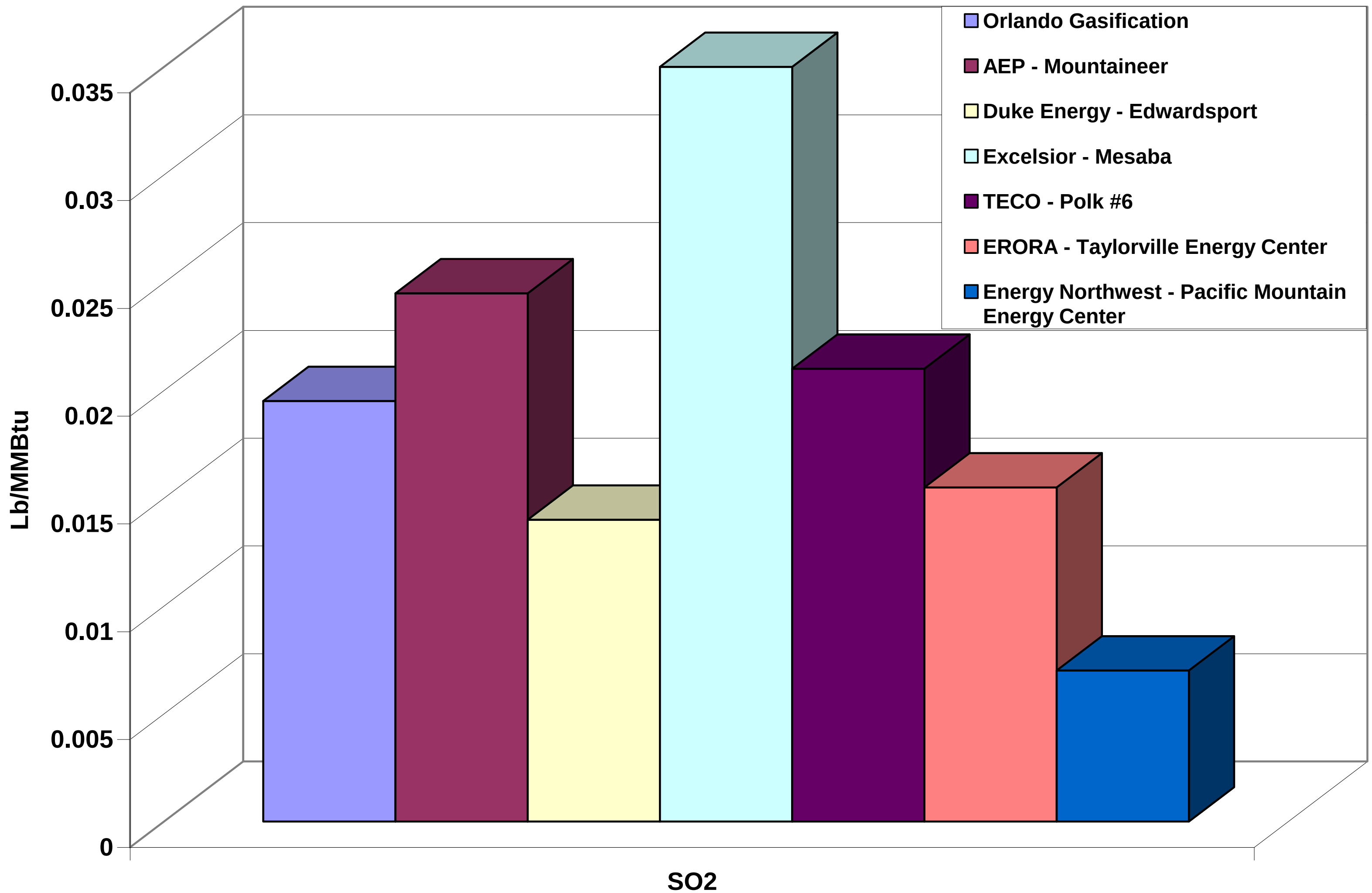
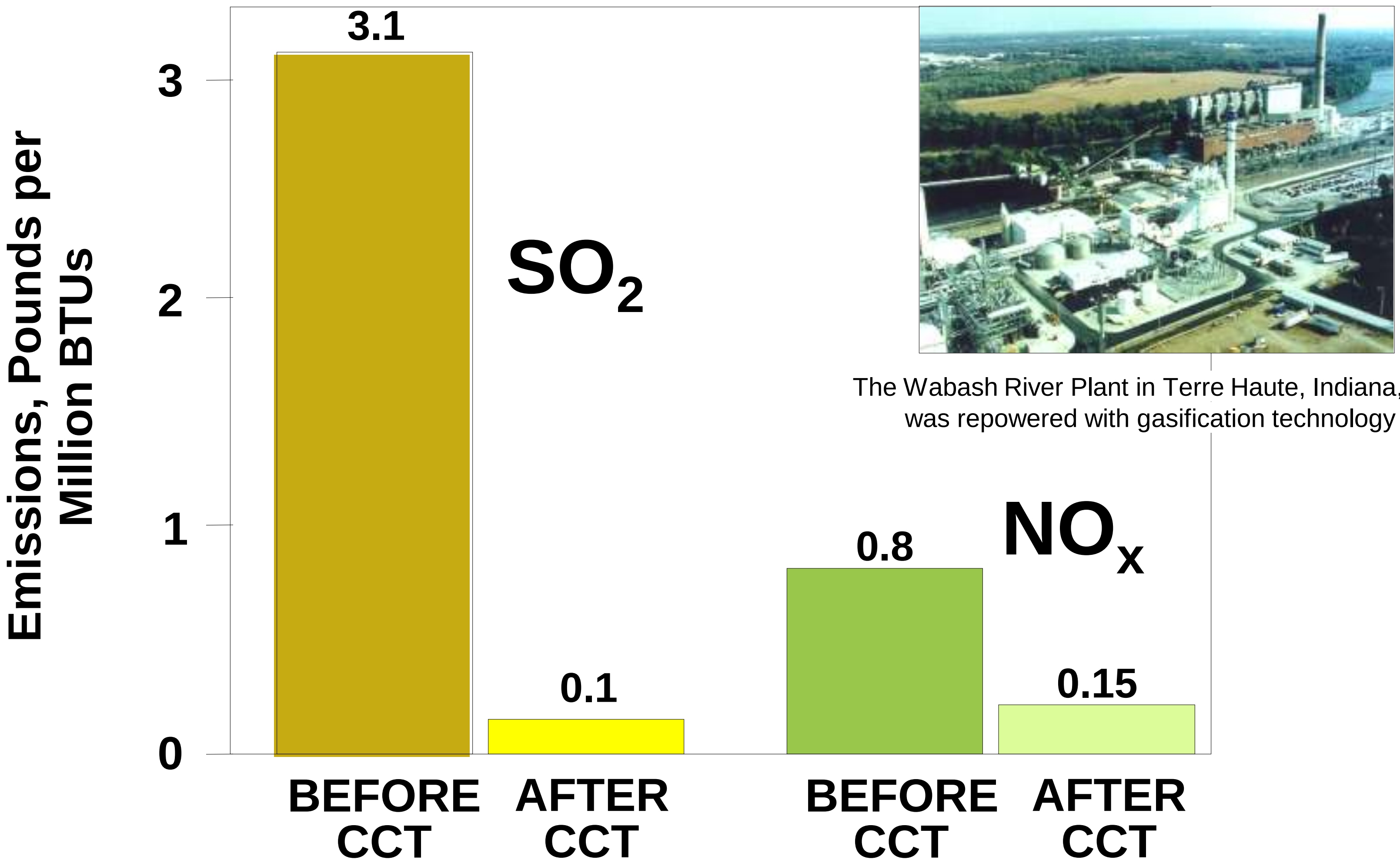
SO_2 Emission Rate Comparisons
Gas Turbine Heat Input Basis



Wabash River Clean Coal Project

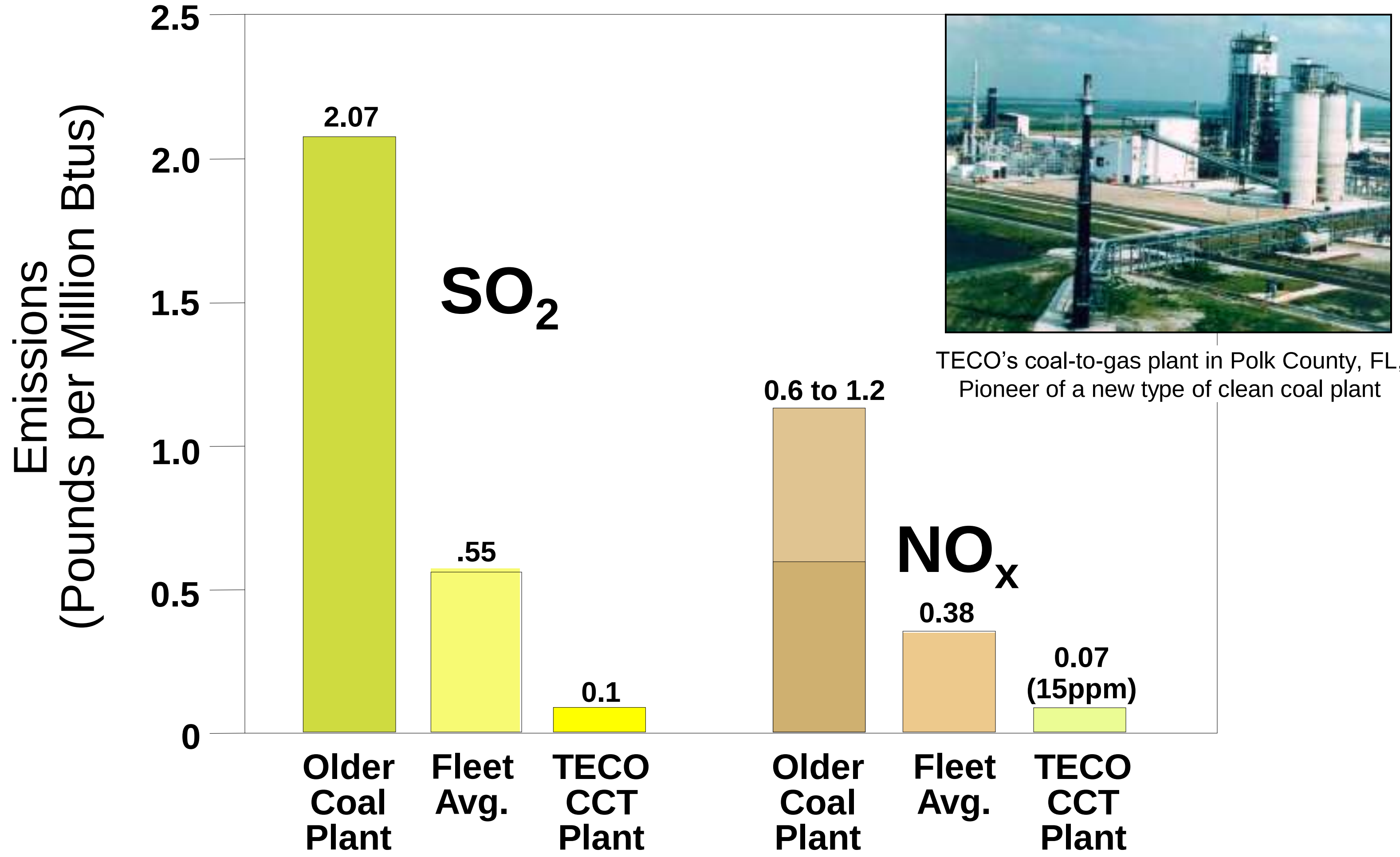
A Case Study for Cleaner Air



The Wabash River Plant in Terre Haute, Indiana, was repowered with gasification technology

Tampa Electric (TECO) Clean Coal Project

A Case Study for Cleaner Air



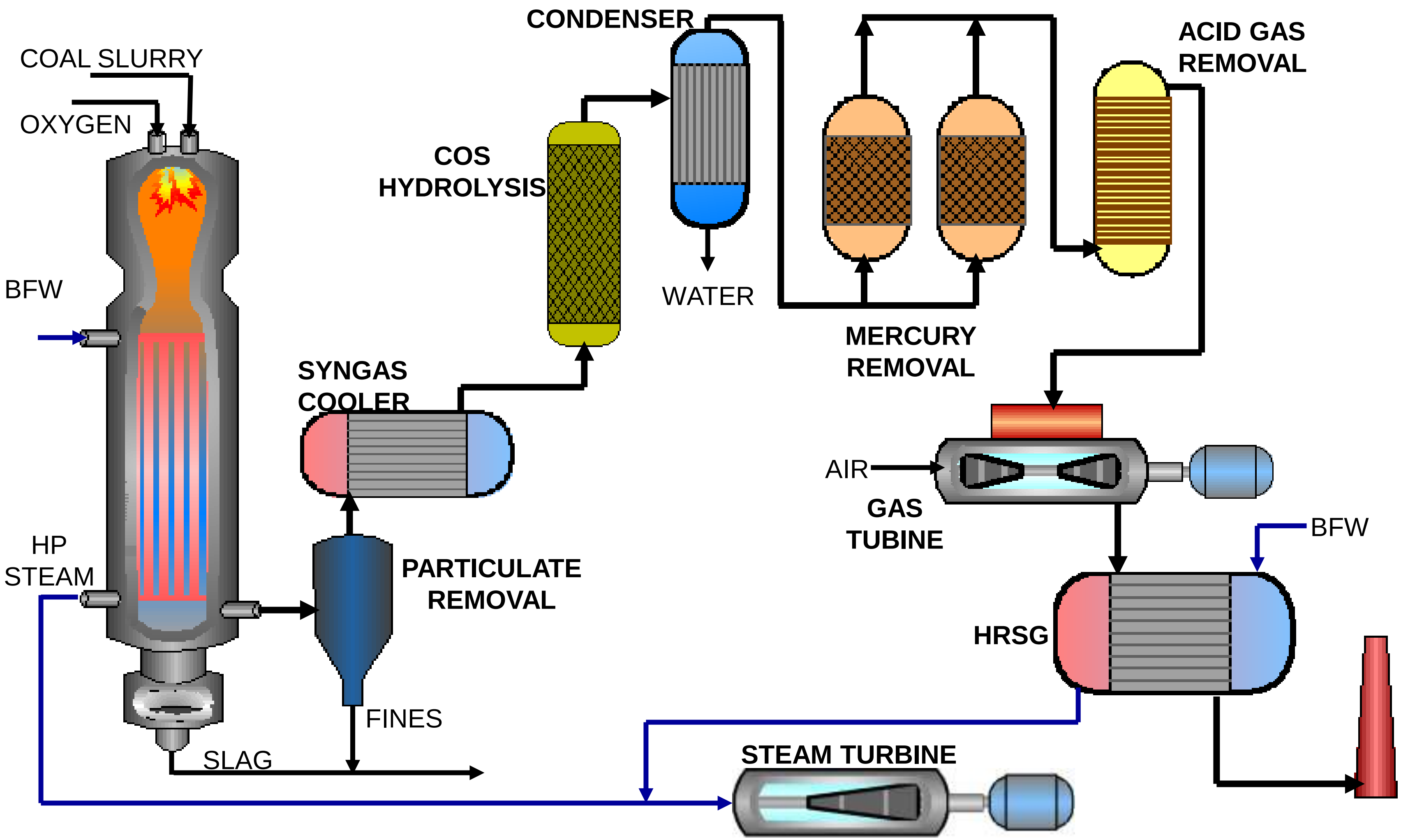
TECO's coal-to-gas plant in Polk County, FL,
Pioneer of a new type of clean coal plant

Active U.S. IGCC Projects

Active Projects	*Location*	*Feedstock*	*MWe*	*Gasifier Vendor*	*CO_2 Capture*	*Planned Operation*
Edwardsport IGCC Project	Indiana	coal	630	GE	STUDY	2012
Kemper County IGCC Project	Mississippi	Mississippi Lignite	582	KBR	67% EOR	2014
FutureGen	Illinois	Illinois bituminous	275	TBD	90% saline formation	2014
Texas Clean Energy Project	Texas	sub-bituminous	400	Siemens	90% EOR	2014
Taylorville Energy Center Hybrid IGCC Project	Illinois	coal	730	GE	50% EOR	2015
Mesaba Energy Project	Minnesota	PRB/petcoke	606	ConocoPhillips	READY	2015
Sweeny IGCC/CCS Project	Texas	petcoke	683	ConocoPhillips	85% depleted gas reservoir	2015
Hydrogen Energy California project (HECA)**	California	coal/petcoke	257	GE	90% EOR	2016
Cash Creek Generation*	Kentucky	coal	630	GE	65% EOR	
Future Power PA	Pennsylvania	coal	150	TPRI	YES	2014
Ohio River Clean Fuels, LLC***	Ohio	coal/biomass	250	Shell	YES	
Somerset Power Plant Retrofit	Massachusetts	coal/biomass	120	WPC	NO[1]	
Great Lakes Energy and Research Park ***	Michigan	coal	250	ConocoPhillips	EOR	
Hyperion Energy Center Refinery and IGCC**	South Dakota	petcoke			90% READY	2014
*also *SNG project, **H2 project, ***CTL project, 1 Use of biomass provides a lower carbon footprint*						

Green highlight indicates project is under construction *Blue highlight indicates a DOE funded project*

IGCC with Mercury Removal



Mercury Removal System
Performance and Cost

- **Remove >90% of mercury**
- **Stable adsorption of mercury in carbon beds as mercury sulfide**
- **Incremental capital costs of $4 – 8/kW for carbon-bed removal system**
- **Incremental cost of electricity of $0.16 – 0.32/MWh for O&M and capital repayment**
  - <0.4% of the cost of electricity (COE) for an IGCC plant where COE is $75 - 80/MWh
  - Estimated cost of mercury removal in IGCC compares favorably (<10%) to costs of 90% removal in conventional PC power plant

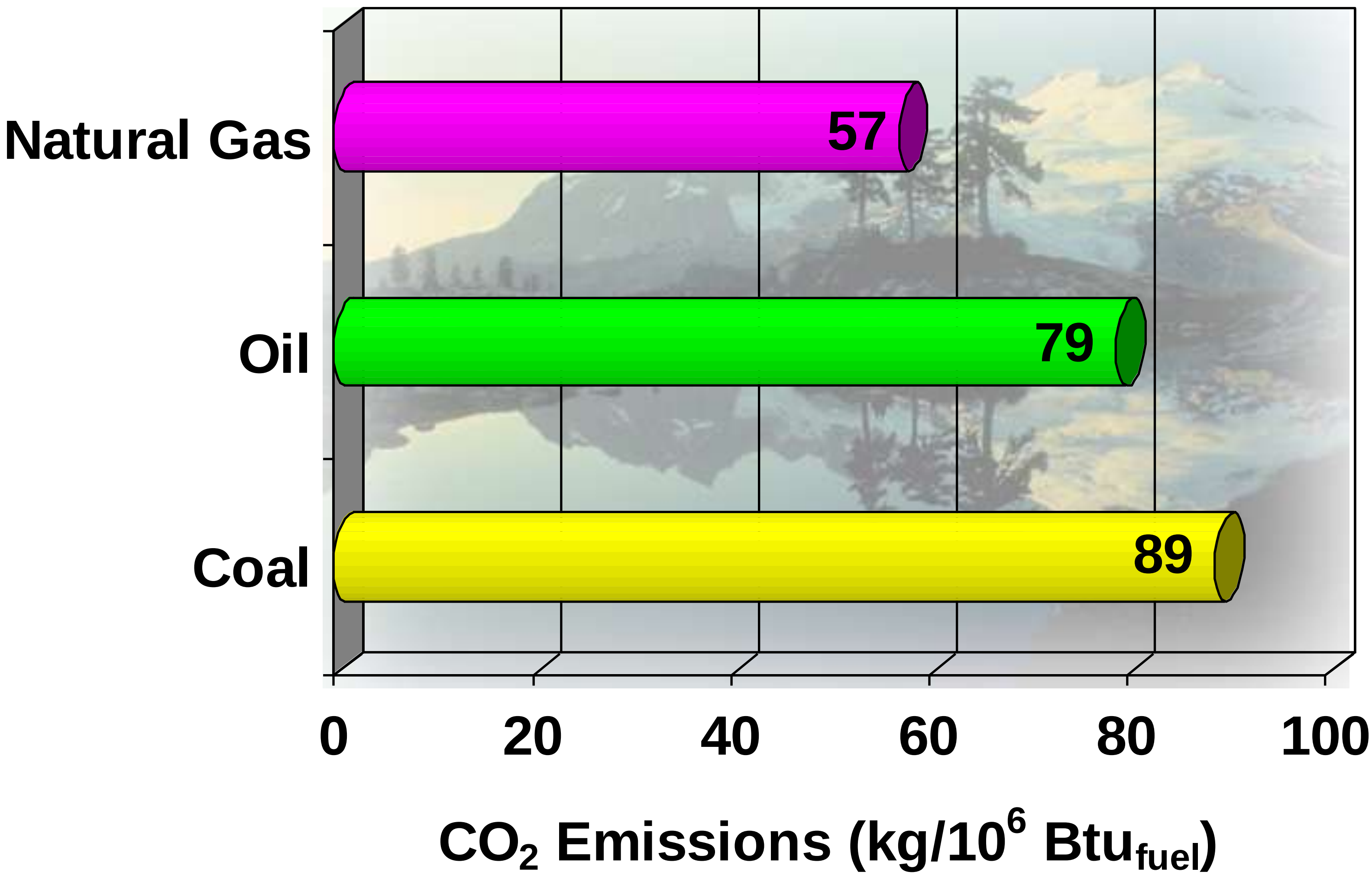
*Estimates for IGCC plant based on the 640 MWe nominal plants used in NETL's "Cost and Performance Baseline for Fossil Energy Power Plants" study**

* http://www.netl.doe.gov/energy-analyses/pubs/Bituminous%20Baseline_Final%20Report.pdf

Gasifier Slag

- **Very similar to slag from coal-fired boilers**
- **It is <u>not</u> regulated as a coal combustion byproduct under RCRA; does not have the same Bevill exclusion from Subtitle C (hazardous wastes)**
- **Gasification slag does have a Bevill exclusion as a <u>mineral processing waste</u>**
- **Mineral processing wastes, as listed in 40 CFR 261.4(b)(7) include:**
  - "Gasifier ash from coal gasification"

Fossil Fuel CO_2 Emissions



Source: NETL Combustion Calculations - HHV Basis

Uncontrolled CO_2 Emissions –
Comparison of Fossil-Fired Power Generation Technologies

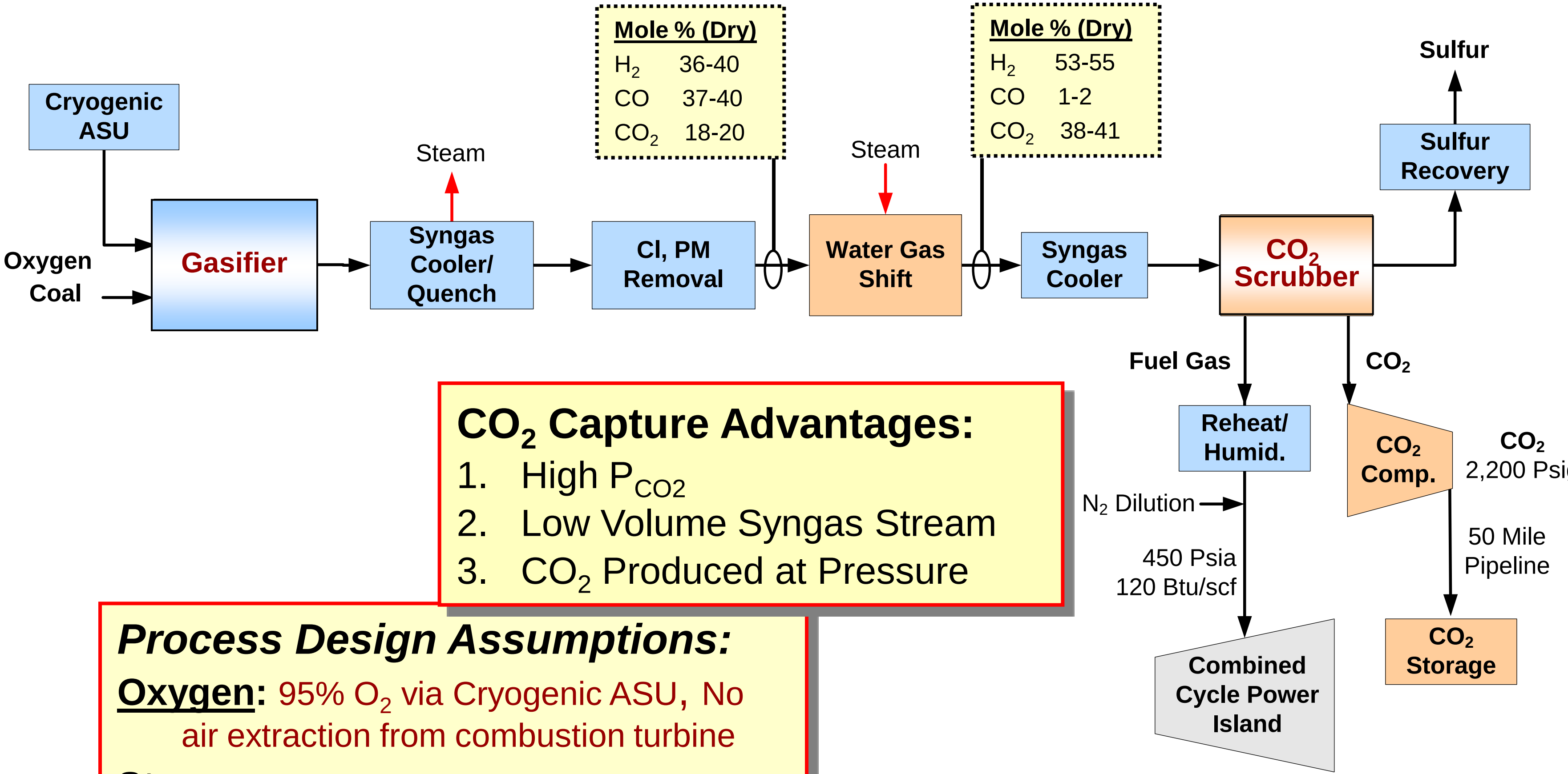
Power Generation Technology	*Heat Rate, Btu/kWh*	*CO_2 Emission, lb/kWh*
Conventional Pulverized Coal-Fired with FGD	9,800	2.00
Pressurized Fluidized Bed Combustion	8,700	1.81
Integrated Gasification Combined Cycle (IGCC)	8,700	1.74
Natural Gas Combustion Turbine (Simple Cycle)	11,000	1.27
Advanced Gasification-Fuel Cell	6,000	1.20
Natural Gas Combined Cycle (NGCC)	7,500	0.86

Volume of CO_2 Produced

- **1 million metric tons of liquid CO_2:**
  - **Every year would fill a volume of 32 million cubic feet**
  - ***Close to the volume of the Empire State Building***
- **U.S. emits roughly 6 billion tons (gigatons) of CO_2 per year**
  - **Under an EIA reference case scenario cumulative CO_2 emissions 2004-2100 are expected to be 1 trillion tons**
  - ***Almost enough to fill Lake Erie twice by the end of the century!***

Pre-Combustion Current Technology

IGCC Power Plant with CO_2 Scrubbing



CO_2 Capture Advantages:

1. High P_{CO2}
2. Low Volume Syngas Stream
3. CO_2 Produced at Pressure

Process Design Assumptions:

Oxygen: 95% O_2 via Cryogenic ASU, No air extraction from combustion turbine

Steam: 1800psig/1000°F/1000°F

CO_2 Compression: 2,200 Psig

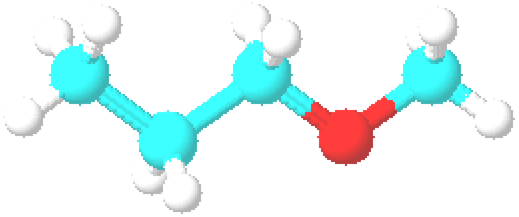
CO_2 Capture via Selexol Scrubbing

Advantages

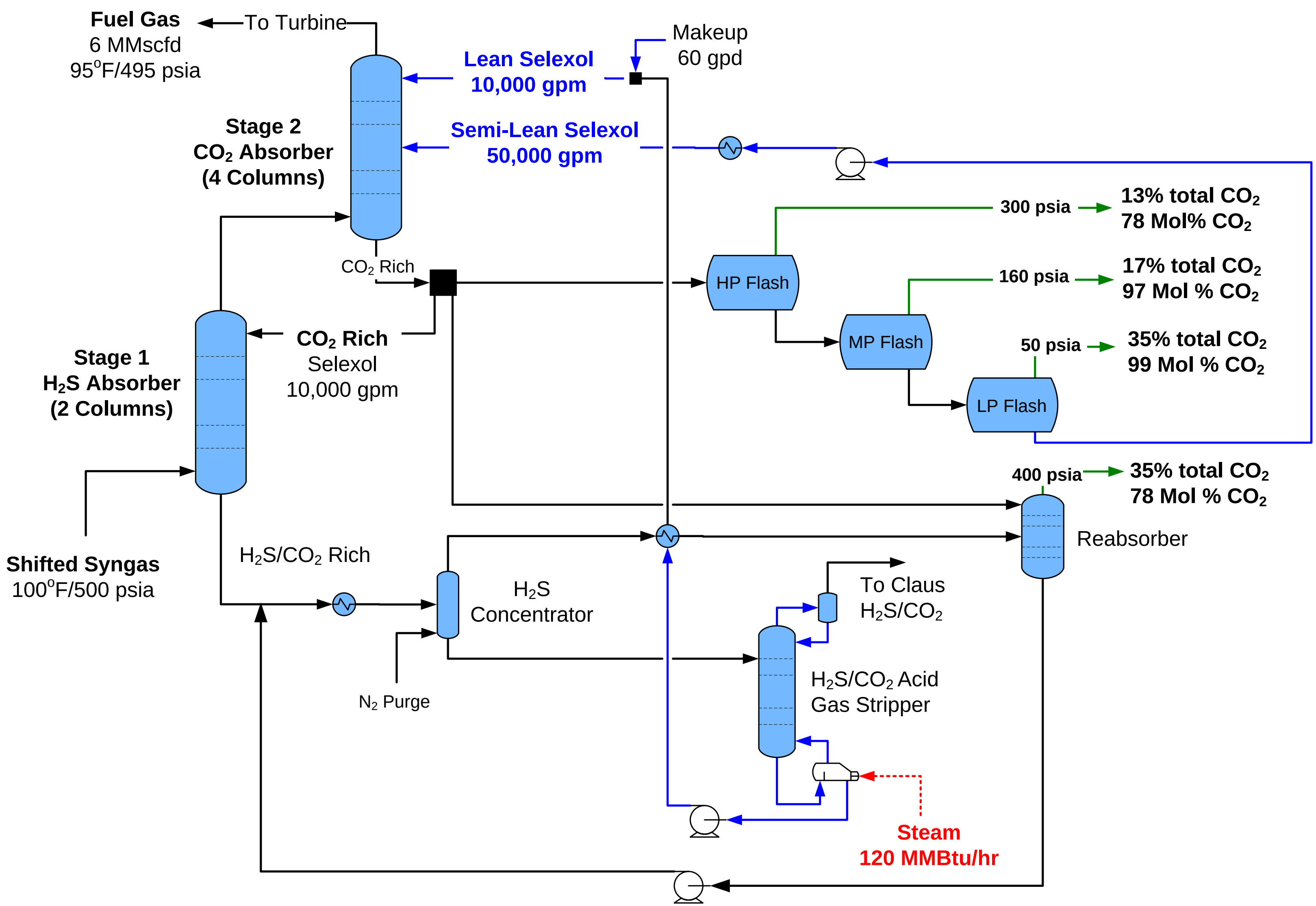
- Physical Liquid Sorbent → High loadings at high CO_2 partial pressure
- Highly selective for H_2S and CO_2 → No need for separate sulfur capture system
- No heat of reaction (ΔH_{rxn}), small heat of solution
- Chemically and thermally stable, low vapor pressure
- 30+ years of commercial operation (55 worldwide plants)

Disadvantages

- Requires Gas Cooling (to ~100ºF)
- CO_2 regeneration by flashing



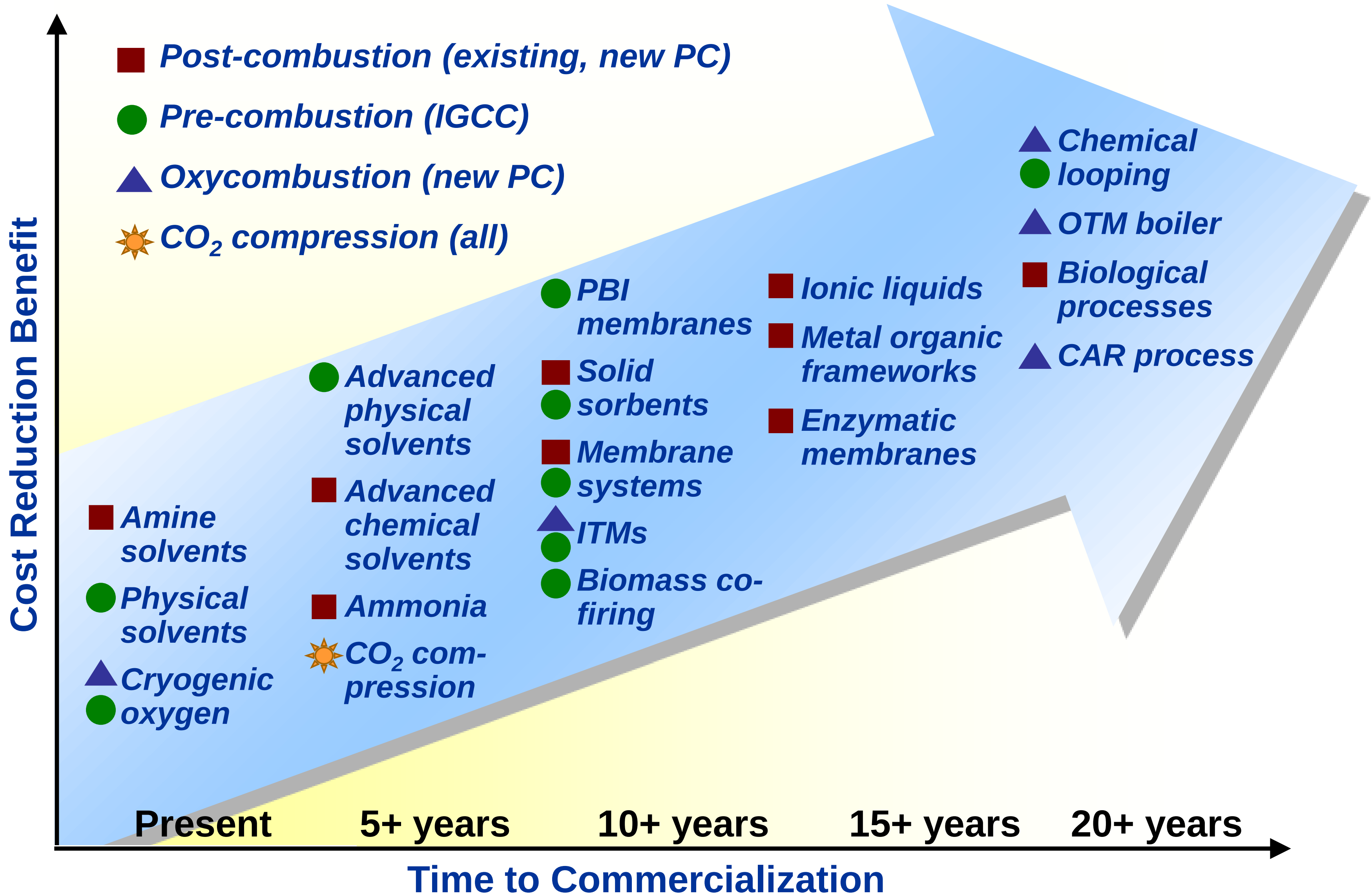
Selexol™ Scrubbing



CO_2 Capture via Rectisol Scrubbing

- **Based on low-temperature (refrigerated methanol)**
- **Capable of deep total sulfur removal as well as CO_2 removal**
- **Most expensive AGR process**
- **Predominantly used in chemical synthesis gas applications**
  - As low as < 0.1 ppmv total sulfur requirements
- **Proposed for use in IGCC for CO_2 removal but no published cost studies**

Technologies for CO_2 Separation



Sample CO_2 Quality Specification

Component	*IPCC, 2005*	*IPCC, 2005; APGTF, 2002*	*Dakota Gasification*	*Kinder Morgan, 2006; Elsam A/S et al., 2003*	*Dixon Consulting; EOR, 2001*	*Industry Working Group, 2005*	*Canyon Reef EOR, 2005*
CO_2 (mole%)	> 95%	> 96%	> 96%	> 95%		> 95%	> 95%
N_2 (ppmv)	< 40,000	< 300	< 6,000	< 40,000	< 20,000	< 40,000	< 40,000
CH_4 (ppmv)	< 50,000	< 7,000	< 20,000	< 50,000	< 10,000	< 50,000	< 50,000
H_2S (ppmv)	< 1,061	< 9,000	< 20,000	< 200	< 100 (ppmv)	< 200	< 1,500
O_2 (ppmv)	< 7.5	< 50	< 100	< 10	< 2 (ppmv)	< 100	< 10
H_2O (ppmv)	< 641	< 20	< 2	< 480	< -5C DP at 300 psia	< -40C DP	< 28lb/MMCF

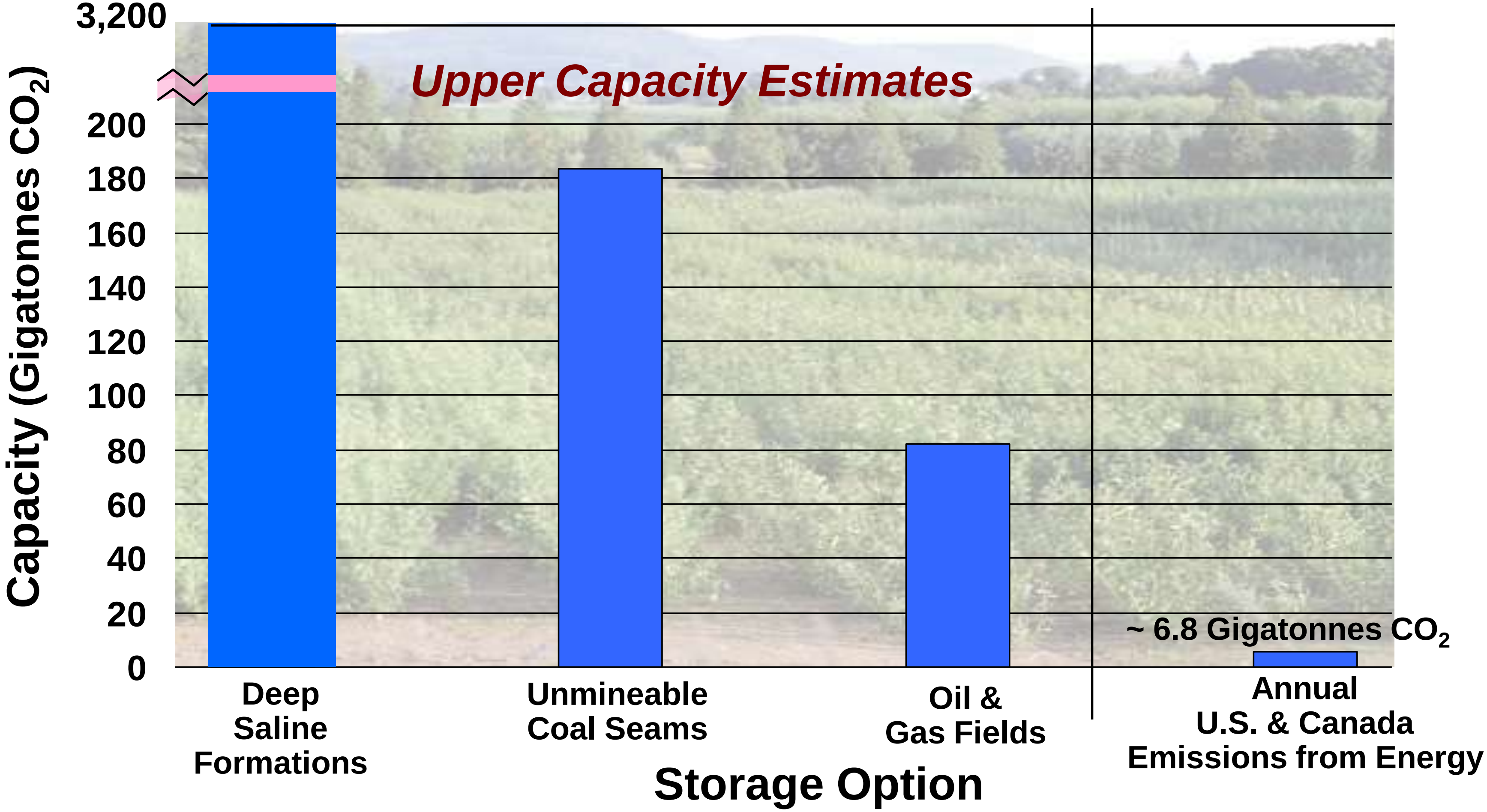
Source: GE Energy

Comparison of CO_2 Storage Options

Characteristics	*EOR*	*Saline Aquifers*	*Depleted Oil & Gas Reserviors*	*Coal Beds*
Experience Base	Permian Basin	Learning	Learning	To date, one failure
Storage Capacity	Moderate	Very high (10-100 x EOR)	Unknown	Low
Leakage Risk	Very low	Low	Very low	High
Accessibility to CO_2 Source	Limited	Extensive	Limited	Very Limited
Likelihood of Success	100%	High	100%	Very low
Economics	Oil production could offset some cost	Gov't incentive required	Gov't incentive required	Gov't incentive required
Overall Risk	Very low	Low	Very low	High
Other Comments	Most EOR projects do not have sufficient demand for CO_2 for one coal fired plant (30 years)	Largest storage capacity opportunity	CO_2 capactiy needs to be quantified	Significant technical uncertainty

From a presentation given by Norm Shilling, General Electric Co, entitled, "IGCC: Its Role in Solving the Carbon Puzzle"

North America Geologic Storage Capacity
(> 500 Year Potential Storage Capacity for U.S. & Canada)

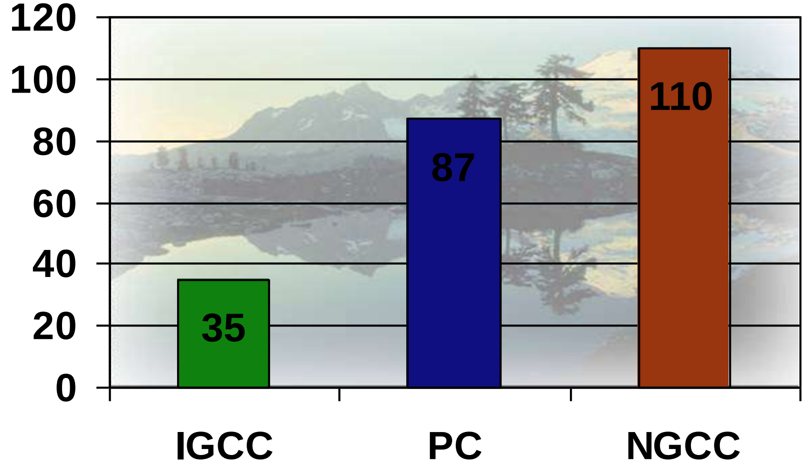


Capacity data source: Carbon Sequestration Atlas of the United States and Canada, DOE-NETL, Feb 2007

Emissions data source: EIA, "International Carbon Dioxide Emissions and Carbon Intensity" extrapolated to mid-2007

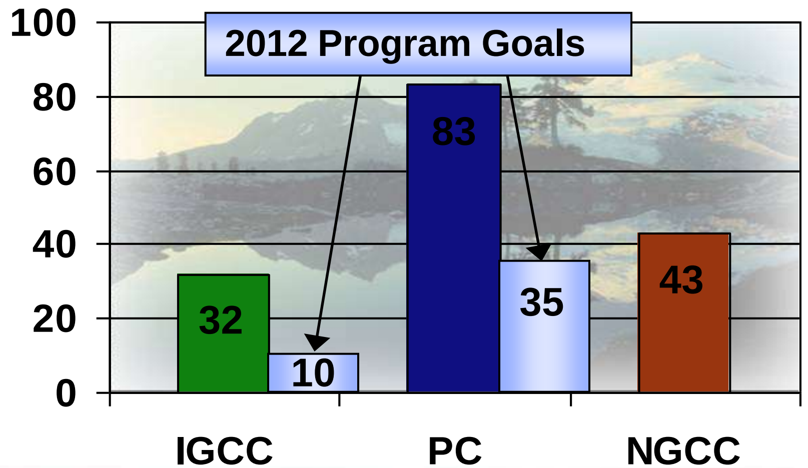
Cost of Carbon Capture

Effect of CO_2 Capture on Capital Cost
(% Increase Resulting from CO_2 Capture)

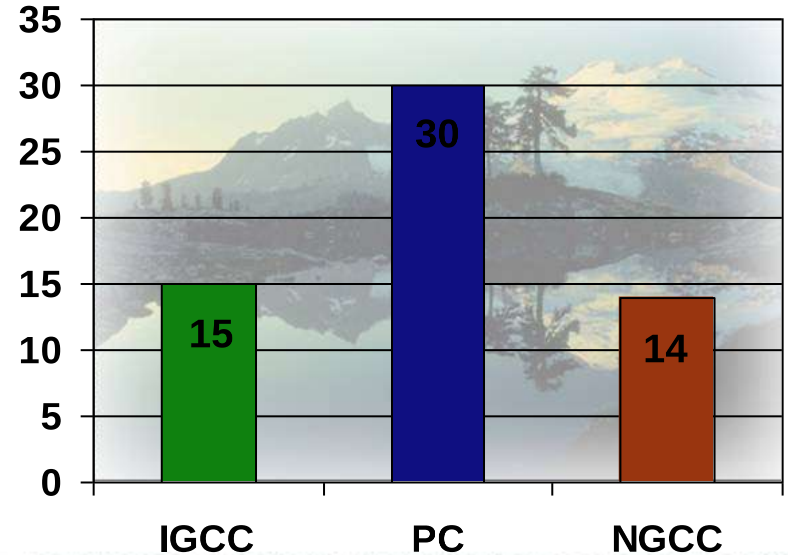


- **35 – 110% increase in capital cost**
- **30 – 80% increase in cost of electricity**
- **15 – 30% energy penalty (reduction in net efficiency)**

Effect of CO_2 Capture on Cost of Electricity
(% Increase Resulting from CO_2 Capture)



Energy Penalty of CO_2 Capture with State-of-Art Scrubbing Technologies
(% Reduction in Net Power Plant Efficiency)



Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity.

DOE Gasification Program Overview

Advanced IGCC Systems Goal

- **2010: Technology Ready for Demonstration**
  - 45 - 47% Efficiency (HHV)
  - $1,600/kWe capital cost
  - 99% SO_2 removal
  - NOx< 0.01 lb/MM Btu
  - 90% Hg removal
- **2015: Technology Ready for Demonstration w/ CCS**
  - 90% CO_2 capture
  - <10% increase in cost of electricity (COE) with carbon sequestration
- **2020: Technology Ready for Deployment**
- **Beyond 2020: Technology Ready for Demonstration**
  - Multi-product capability (e.g, power + H_2)
  - 60% efficiency (measured without carbon capture)

Advanced IGCC Systems Roadmap

Challenges

Optimization of Coal Use with
- Zero emissions
- High efficiency
- Low cost plants

for production of
- Electric power
- Fuels
- Chemicals
- Hydrogen

Reduction of Power Plant Pollutants (NOx, SOx, Hg, As, Cd, Se, PM)

Reduction of CO_2 Emissions

Maintain Low Cost of Electricity to the Public through diversified mix of indigenous fuels

R&D Pathways

By 2010
- Transport gasifiers
- Advanced materials & instrumentation
- Dry feed pump
- Warm gas cleaning
- 7FB gas turbines
- ITM oxygen
- 85% capacity factor
- 98% carbon conversion

By 2015
- Hydrogen gas turbines
- 90% capacity factor
- CO_2 capture & sequestration

By 2020
- Chemical looping gasifiers
- SOFC topping cycle
- Advanced gasifiers
- Underground coal gasification
- Multi-product capability

Targets

By 2010
- Net plant efficiency, 45-47% (HHV)
- Capital cost, $1600/kW*

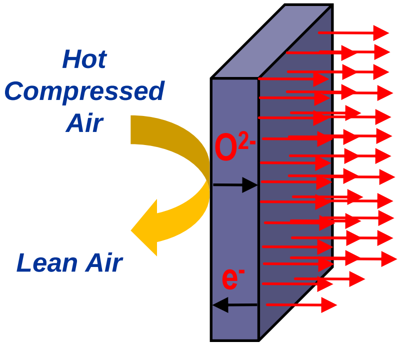
By 2015
- IGCC technology with 90% CO_2 capture resulting in less than 10% increase in COE

By 2020
- Technology ready for deployment & demonstration
- Multi-product capability (e.g. power + H_2)
- Net plant efficiency, 60% (HHV)**

*Cost in 2007$
**Targets for Plants w/o Carbon Capture

Major Gasification Technology Issues

Oxygen Membrane



Oxygen

- Membrane reliability
- Process integration
- Manufacturing

- Low-rank Coal

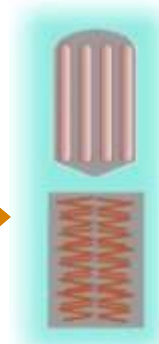
Coal

- Injector reliability
- Single train availability
- Refractory durability
- Alternative feedstocks
- Feed system reliability
- Heat removal/integration
- Temperature measurement & control

Gasification

Fuel Gas

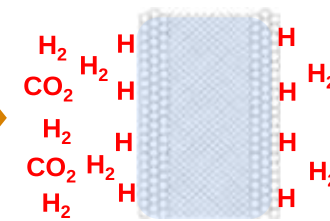
Gas Cleaning



- Cost-effective multi-contaminant control
  - elevated temperatures (300 – 900°F)
- Downstream process requirements
- Integration with NOx reduction processes
- Process intensification

Water-Gas Shift

- Process intensification
- Integration with H_2 separation device



H_2 Rich Stream

H_2/CO_2 Separation

CO_2

- Membrane /sorbent durability
- Contaminant sensitivity

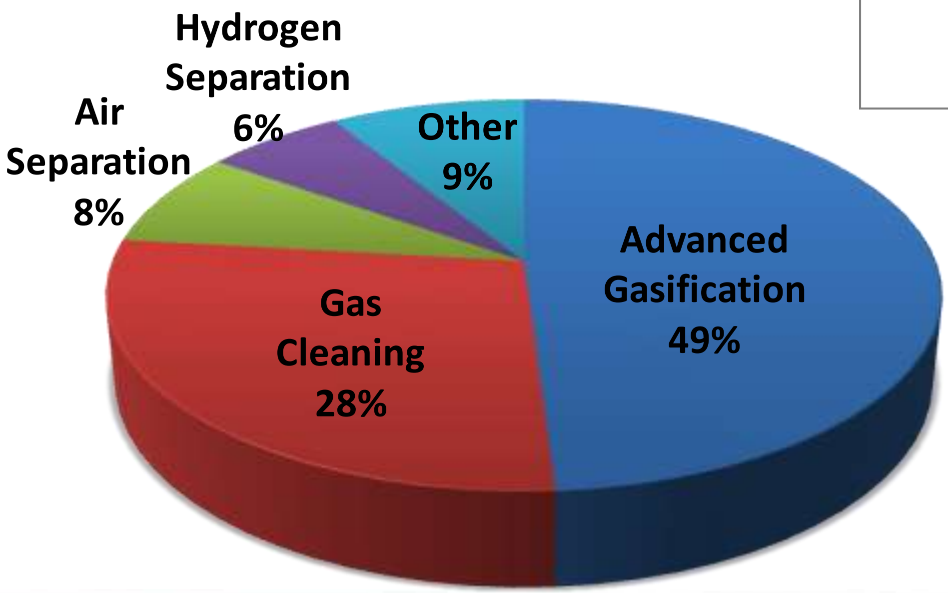
FY10 Gasification Technology Program

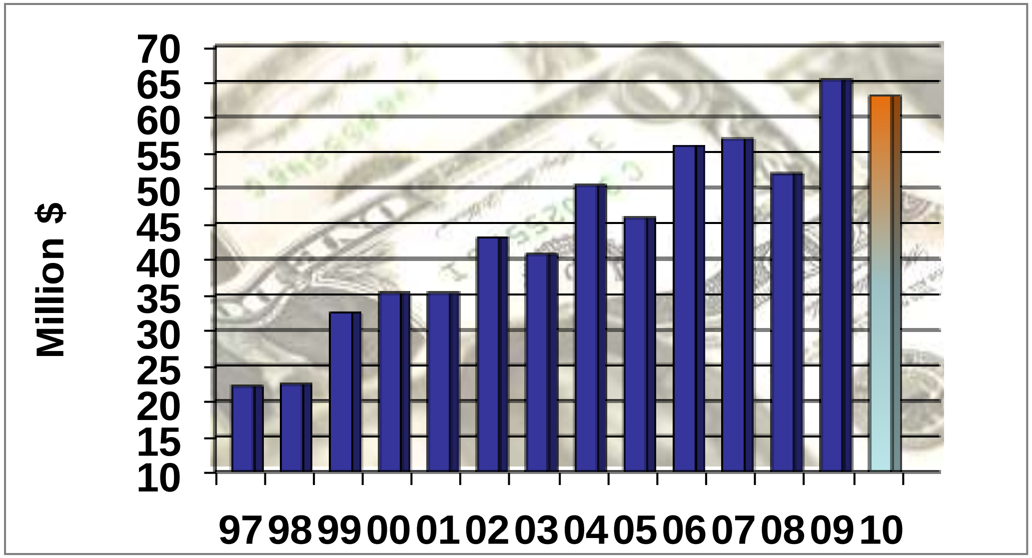
16 Projects

Organizations

• Industry	4
• National Laboratories	1
• Not-for-profit	2
• Universities	1
Total	8

FY10 Budget Allocation





Annual Budget

Advanced Gasification Technologies

Oxygen Production - Ion Transport Membranes (APCI)

- Operating full-scale modules – 5 TPD unit
- Detailed design/construction of 150 TPD unit in progress
  - *commissioning scheduled 2Q FY 2011*
- 2,000 TPD unit planned for 2015/16

0.5 TPD ITM Modules

Coal Pump - Linear Extrusion Coal Feed Pump (PWR)

- Detailed design of 600 TPD pump in progress
- Commissioning scheduled 4Q 2010

Pump Concept

Warm Gas Cleanup - High Temperature Gas Cleaning (RTI)

- 50 MWe transport desulfurizer at TECO with option for integrated high temperature CO_2 capture
- Commissioning scheduled 2Q FY 2012

Unit at Eastman Chemical

Hydrogen Separation - Hydrogen/Carbon Dioxide Membrane (Eltron)

- Eastman Chemical – Development partner (in negotiations)
- Current testing at 1.5 lb/d H_2
- Scale-up 12 lb/d – 2010; 220 lb/d – 2011/12 (tentative)

1.5 lb-day H_2 Membrane

National Carbon Capture Center at the Power Systems Development Facility (PSDF)

Wilsonville, AL

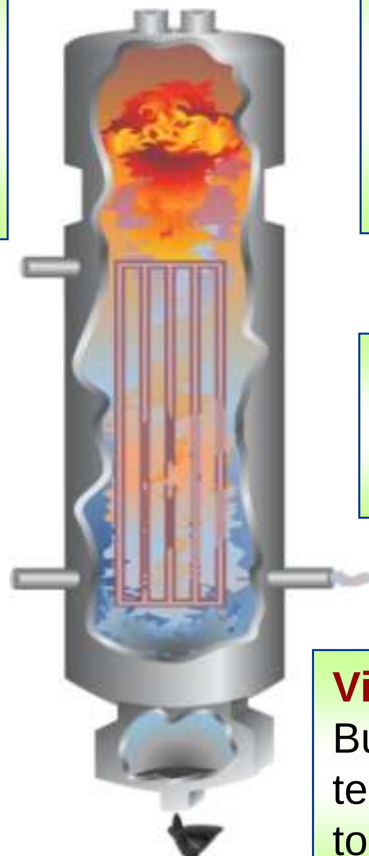
- **Southern Company**
  - American Electric Power
  - Arch Coal
  - Electric Power Research Institute
  - Luminant
  - NRG
  - Peabody Energy
  - Rio Tinto

Development and commercial scale-up of modular industrial scale gasification-based processes and components

Gasification Systems

NETL
Office of Research and Development
On going investigations into the co-gasification of coal and biomass including biomass feed preparation

GE Energy
Engineering a predictive control model for advanced system control to increase plant reliability and performance



Southern Company Services
National Carbon Capture Center
Cultivating technologies that will lead to the commercialization of cost effective advanced coal fueled power plants with CO_2 capture

Pratt & Whitney Rocketdyne
Development and testing of a high pressure coal feed pump

Virginia Polytechnic Institute
Building an accurate and reliable temperature measurement device to enable improved gasifier control

National Carbon Capture Center

Project Goal:

Develop technologies that will lead to the commercialization of cost effective advanced coal fueled power plants with CO_2 capture

National Carbon Capture Facility

Status:

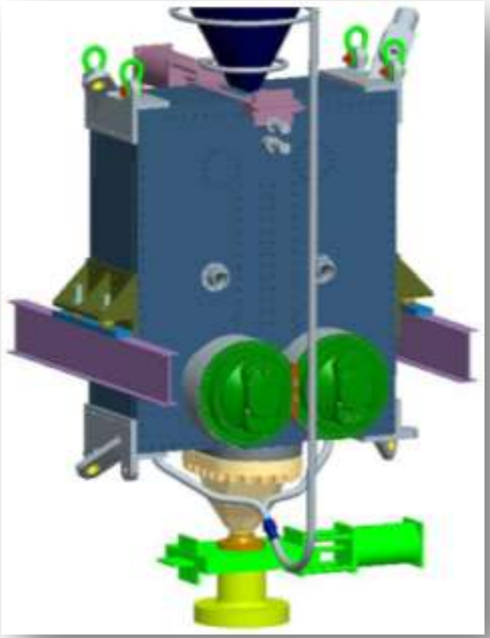
- 12,600 hours of coal gasification
- Two 500 hour gasification test runs completed/Third underway Nov'09
  - R01, Mississippi lignite, carbon conversions to +99% & fluid bed drying system reduce moisture from 42% to 18%
  - R02, PRB/ R03, PRB with biomass near end
- PCD Development- New type filter elements tested (Porvair)
- Pressure Decoupled Advanced Coal (PDAC) Feeder
  - Modifications to improve feed rate variability and control logic
  - Operated 400 hours in R02 with improved gasifier temperature standard deviation
- Biomass
  - Assessed biomass availability
  - Off-line feeder testing at gasifier operating pressure
  - Lab studies- ash chemistry, tar production, & corrosion concerns
  - Coal/biomass co-feed gasification test planned for Dec. 2009
- Sensor
  - Improvements in gasifier thermowell performance
  - Development of reliable coal feed rate measurement
- 1,500 lb/hr syngas cleanup (SCU) slipstream operated
  - Test fuel cell, H_2 membranes and Hg sorbent
  - WGS catalytic filter element testing
  - WGS steam/CO optimization
  - SCU upgrade allows independent operation & control of vessels

High Pressure Solids Pump

Benefit:
- Reduce heat penalties with slurry feed and high-moisture (western) low-rank coals

Two approaches:
- Pratt Whitney Rocketdyne (PWR): linear flow geometry
- Stamet: cylindrical flow geometry (purchased by GE 2007)

Common principle:
- Uses pulverized coal under mechanical pressure to maintain high pressure seal to gasifier



PWR Pump
utilizes linear flow geometry

PWR Status:

Pump design activity
- Pump component testing nearly complete
- Developed dry solids pump design criteria
- Final design of prototype pump underway
- Testing begins 4Q 2010 at EERC

Determination of effects of biomass/coal blends on solid feed systems
- Analyze coal/biomass blends to predict transport behavior
- Conduct gasification economic analysis
- Model feed system and pump using test data
- Select most promising blend for further testing
- 600-tpd pump testing at EERC

Gasifier Performance and Capital Cost Summary

with and without coal feed pump

	Shell Gasifier		Transport Gasifier		GE Energy R/C Gasifier	
Coal Type / Feed Type	Eastern		Western		Eastern	
Coal Preparation for Feed	Drying	Pump	Drying	Pump	Slurry	Pump
Auxiliary Power, MWe	43.2	44.2	35.8	39.9	49.0	44.0
Net Plant Efficiency (HHV)	40.6%	40.9%	40.5%	40.7%	40.4%	40.9%
Net Heat Rate (Btu/kWhr)	8,410	8,345	8,416	8,386	8,456	8,335
Total Coal Prep Capital Cost ($x1000)	$45,590	$17,898	$59,594	$33,279	$12,766	$9,751
Total Coal Prep Capital Cost ($/kW)	$176	$69	$197	$111	$46	$37
Total Gasifier Island Cost ($/kW)	$611	$501	$438	$352	$449	$463

Coal Feed Pump Favorable

Coal Feed Pump Less Favorable

Advanced Gas Separation

Eltron Research
Developing materials to separate hydrogen from syngas

Research Triangle Institute
Development of novel chemical looping technology for co-production of hydrogen and electricity

Air Products and Chemicals, Inc.
Developing and demonstrating ion transport membranes (ITM) for oxygen production

Ohio State University
Development of novel iron-based chemical looping technology for IGCC and Fischer-Tropsch Applications

Ion Transport Membrane Air Separation

0.5 TPD Modules

Air Products & Chemicals
Ion Transport Membrane
"ITM Oxygen"

Subscale Engineering Prototype (SEP) ITM Test unit at APCI's Sparrows Point gas plant

(ITM capacity: 4,550 sTPD oxygen)

	ITM Oxygen	Cryo ASU	Δ%
IGCC Net Power (MWe)	627	543	+15
Net IGCC Efficiency (% HHV)	38.9	38.4	+1.2
Oxygen Plant Cost ($/sTPD)	18,700	25,000	- 25
IGCC Specific Cost ($/kW)	1,368	1,500	- 9

ITM Benefits: IGCC plant specific capital cost reduced by 9%, plant efficiency increase by 1.2%, with ~25% cost savings in oxygen production

Photos: Air Products and Chemicals, Inc. 2006

APCI Air Separation ITM Modules

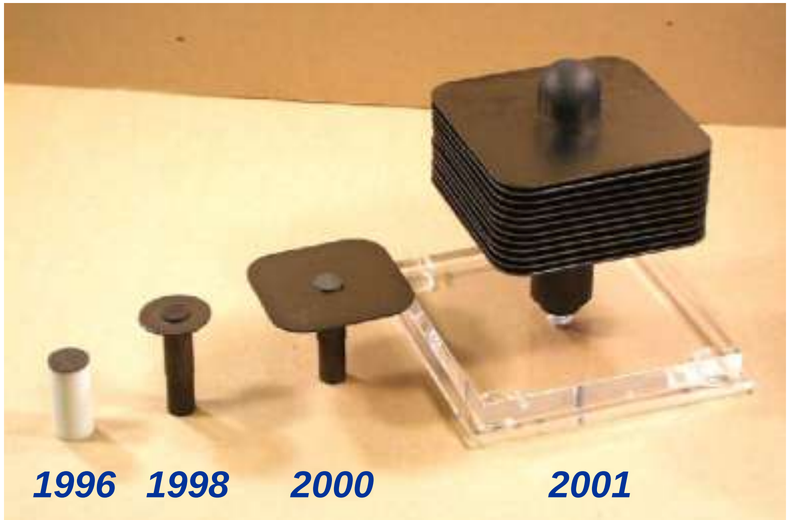
- **Testing of 5 TPD SEP unit**
  - Operated under full driving force conditions
  - Met/exceeded wafer performance for flux and purity
  - Cycled modules from idle to operating conditions w/o loss of performance
- **Proved feasibility of full integration with large frame GTs**
- **Phase 3 underway – design, construction, and operation of a 150 TPD Intermediate Scale Test Unit (ISTU) facility.**
- ***Planning Phase 4***
  - *1,500 to 2,500 TPD unit*

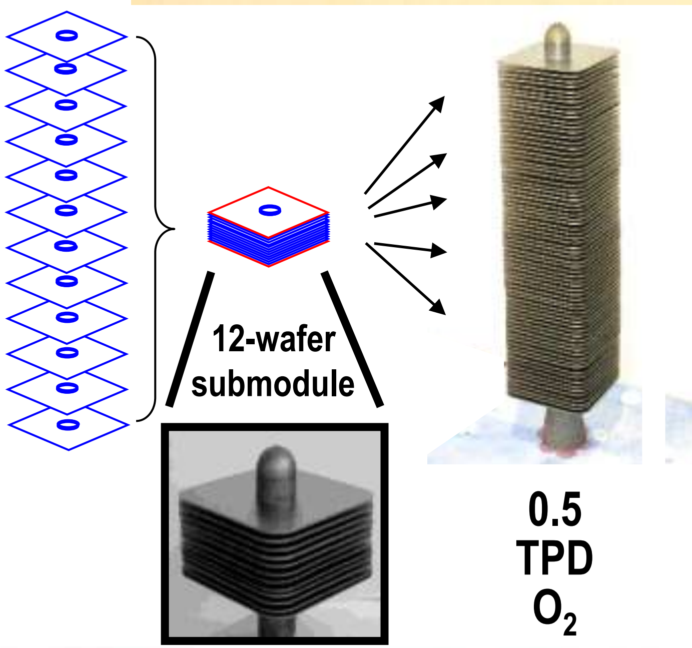
Subscale Engineering Prototype (SEP) ITM Test unit at APCI's Sparrows Point gas plant

0.5 TPD Modules

- **Test membrane modules**
  - FY06 – 5 TPD (successfully completed)
  - FY11 – 150 TPD
- **Offer commercial air separation modules**
  - Post FY12 – Spinoff applications
  - Post FY16 – IGCC demos

Membrane Fabrication and Scale-Up





0.5 TPD Stack

2005

1.0 TPD Stack

2008

Membrane Air Separation Advantages

Air Products

(ITM capacity: 4,550 sTPD oxygen)

	ITM Oxygen	Cryo ASU	Δ %
IGCC Net Power (MWe)	627	543	+15
Net IGCC Efficiency (% HHV)	38.9	38.4	+1.2
Oxygen Plant Cost ($/sTPD)	18,700	25,000	- 25
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Co-Production of Electricity and Hydrogen

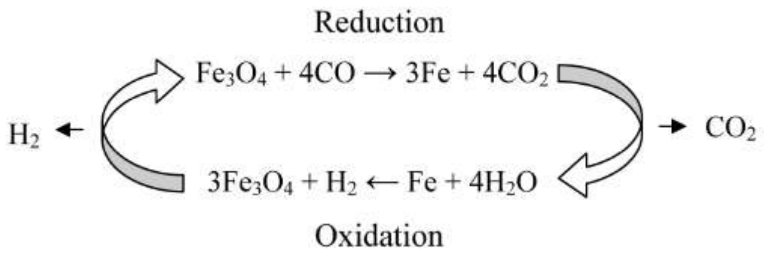
RTI International

Goal:

Develop a highly efficient steam-iron process technology for the co-production of electricity and hydrogen in an integrated gasification combined cycle (IGCC) power plant

Accomplishments:

- Iron (FE)-based catalysts synthesized and compositions have been manipulated to improve hydrogen production
- Synthesized catalysts were tested in a fluidized-bed microreactor system
- A performance evaluation was performed and an optimal catalyst composition selected



Hydrogen produced by steam-iron redox cyclone *using a novel iron-based catalyst*

Benefits:

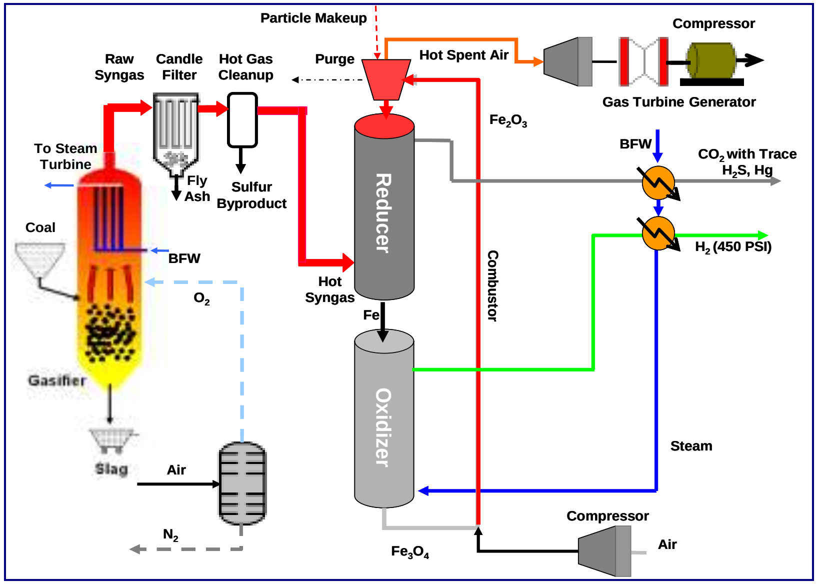
Enable co-production of high purity hydrogen and electricity from an IGCC at an economic level

Enhanced Hydrogen Production

Integrated with CO_2 Separation

Goal:
Develop a process that produces a pure hydrogen stream and a concentrated CO_2 stream in two separate reactors — avoiding additional CO_2 separation cost

Benefits:
Enable co-production of high purity hydrogen and electricity from an IGCC at an economic level



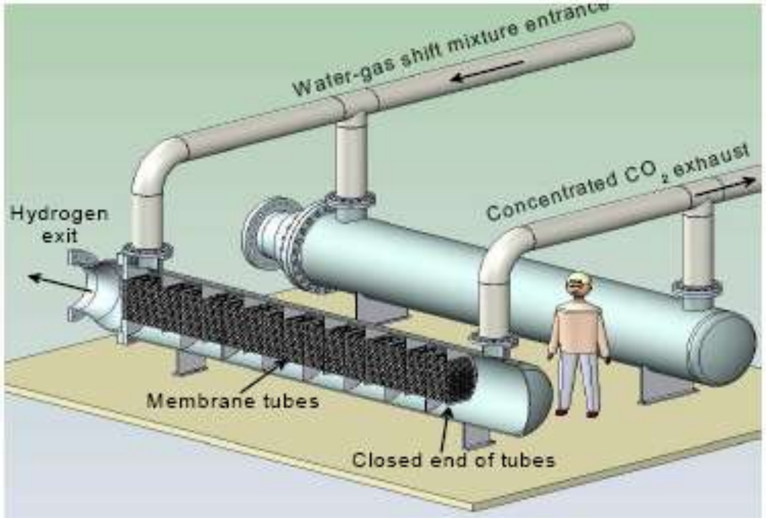
Simplified schematic of the Syngas Chemical Looping Process for H_2 production from coal

Ohio State University

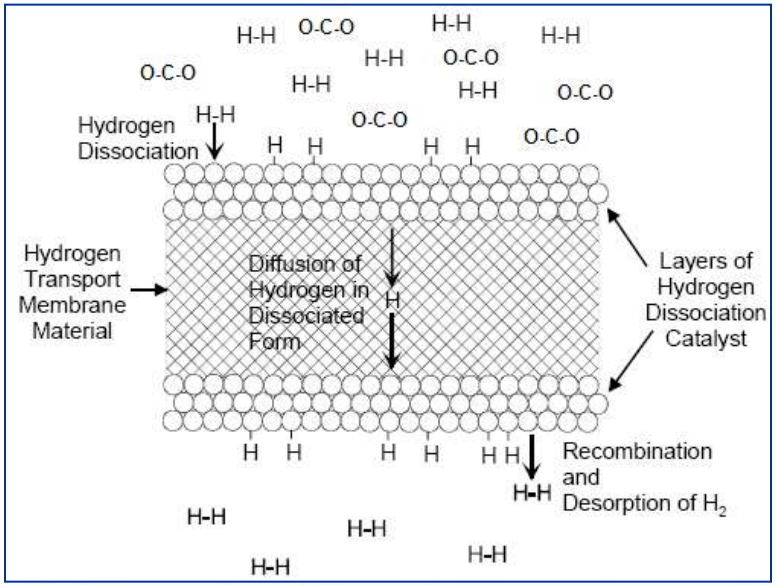
ELTRON Hydrogen Membrane

Description

- Allows capture of high pressure CO_2
- High hydrogen permeate pressure
- High hydrogen recoveries >90%
- Essentially 100% pure hydrogen
- Low cost
- Long membrane life
- Target: 4 tpd module in 2013 / 2014



Conceptual design of a commercial membrane unit capable of separating 25 tons per day of hydrogen.



Status

- Seeking development partner
- Current testing at 1.5 lb/d
- Scale-up to 12 lb/d – 2010
- Scale-up to 220 lb/day – 2011/12

Eltron Research & Development Tech Brief http://www.eltronresearch.com/docs/Hydrogen_Membrane_Technology_Summary.pdf

Progress Towards DOE-FE Targets

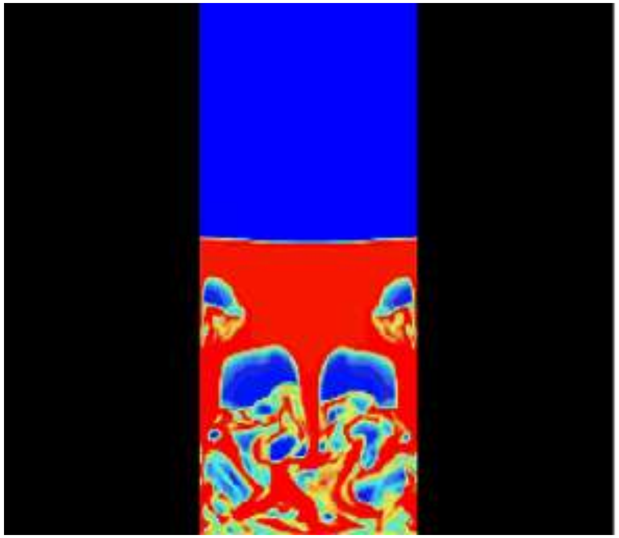
Performance Criteria	*2005 Target*	*2010 Target*	*2015 Target*	*Current Eltron Membrane*
Flux (sccm/cm^2/100 psi ΔP)	**50**	**100**	**150**	160
Operating Temperature (^{o}C)	**400-700**	**300-600**	**250-500**	**300-400**
S Tolerance (ppmv)	**N/A**	**2**	**20**	20 (early)
System Cost ($/ft^2)	**1000**	**500**	**<250**	<200
ΔP Operating Capability (psi)	**100**	**400**	**800-1000**	1,000
Carbon Monoxide Tolerance	**Yes**	**Yes**	**Yes**	Yes
Hydrogen Purity (%)	**95**	**99.5**	**99.99**	>99.999
Stability/Durability (years)	**1**	**3**	**>5**	**0.9**
Permeate Pressure (psi)	**N/A**	**N/A**	**N/A**	*270*

Improving Process Control

Modeling & Monitoring Systems in Harsh Environments

NETL
Office of Research and Development
Development of new refractory materials

NETL
Office of Research and Development
Development of an IGCC Dynamic Simulator



Hydrodynamics in the Bubbling Fluidized Oxidation Reactor

Virginia Polytechnic Institute
Development of a single crystal sapphire optical fiber sensor for reliable temperature measurements in slagging coal gasifiers

Gas Technology Institute (GTI)
Development of an optical sensor for monitoring coal gasifier flame characteristics

NETL
Office of Research and Development
Computational Fluid Dynamics (CFD) modeling of advanced gasifiers

IGCC Dynamic Simulator & Research Center

Office of Research and Development

- **Mission: "IGCC with CO_2 capture" research, demonstration, education, and training**
- **Objective: Full-scope, high-fidelity, real-time dynamic simulator**
  - Start-ups, shutdowns, and load changes
  - Normal, abnormal and emergency operating conditions
  - Full DCS emulation and control strategy analysis
  - Instructor station, scenarios, trending, snapshots, etc.
- **Location**
  - Flagship research center at NETL
  - Training and education center at WVU's National Research Center for Coal & Energy (NRCCE)
- **Operation**
  - NETL Institute for Advanced Energy Solutions (IAES)
  - Collaboratory for Process & Dynamic Systems Research
- **NETL Collaboration Partners**
  - Invensys Process Systems/West Virginia University
  - Fossil Consulting Services, Enginomix, EPRI/CoalFleet
- **Current Status**
  - Development phase initiated in Q1FY2009
  - Establish the Dynamic Simulator Research & Training Center and Deployment of the IGCC Dynamic Simulator in FY2010

Process Training Simulator (Source: Invensys Process Systems)

Planned Configuration for NETL IGCC Dynamic Simulator

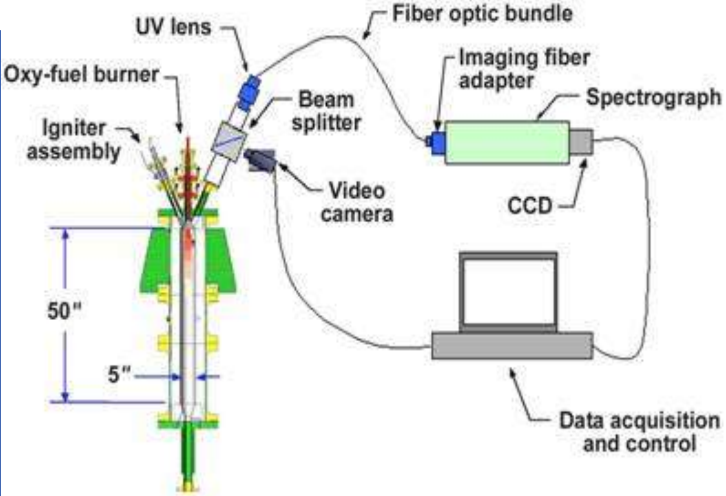
Real-Time Flame Monitoring Sensor

Gas Technology Institute

Field Test Objective:
Develop a reliable, practical, and cost-effective means of monitoring coal gasifier feed injector flame characteristics using an optical flame sensor

Accomplishments:

- Modified sensor to detect UV, visible, and/or near IR wavelengths
- Successfully completed lab-scale testing with natural gas flames
- Successfully tested the sensor on a natural gas mockup of an oxygen-fired, high pressure pilot-scale slagging gasifier

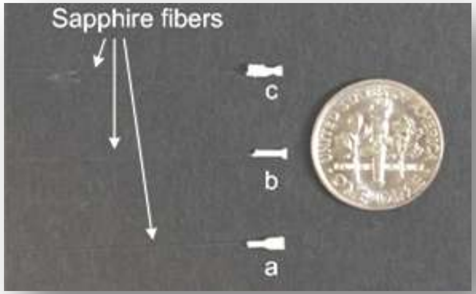


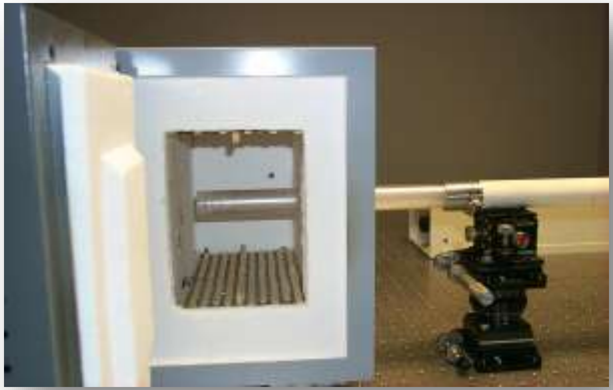
Instrumentation used for accessing CETC gasifier flames using fiber optic coupling

Future Work:
Field demonstration tests at the GTI pilot-scale gasifier

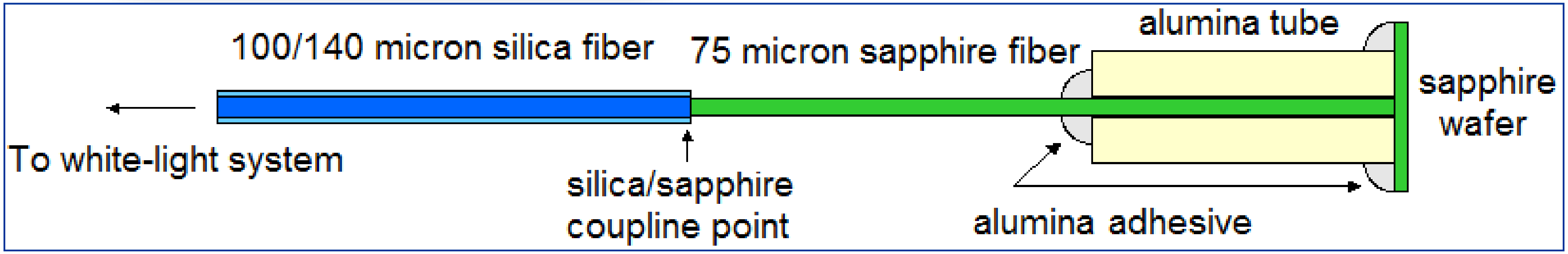
Single Point Sapphire Temperature Sensor
Virginia Polytechnic Institute

Accomplishments
- Accurate readings up to 1600 °C
- Methods, fabrication, designs, and packaging under development since 1999
- Full-scale testing at TECO
- 7 months of operation





Status
- Additional long-term testing planned at Eastman Chemical
- IP and licensing being evaluated by Virginia Tech
- Considering testing on turbines (combustor section)



Warm Gas Cleanup Progress

RTI Process Development Testing at Eastman Chemical

Field Test Objective:

Successfully test warm-gas multi-contaminant cleanup technologies – while creating pure sulfur product – using coal-derived syngas

Preliminary Slipstream Test Results:

- >3,000 hr of sulfur removal – as low as 1 ppm
- Equally effective on H_2S and COS
- Stable solids circulation at 300-600 psig
- Low sorbent attrition
- >500 hr pure sulfur production from process off gas
- Tested multi-contaminant removal for NH_3, Hg, and As

Future Plans:

- 50 MWe slip stream demonstration unit being designed for Tampa Electric 's 250-MW IGCC power plant
- NETL economic analysis show potential:
  - ✓ 2-4 point improvement in plant efficiency
  - ✓ 4% reduction in COE

WGDS Operations Summary

September 2006 to November 2007

- **Reached Steady State Regeneration within 10 hours of startup on 9/5/06**
- **3017 hours of Syngas Operations**
  - 346 hr longest continuous run
  - 61-81% On-Stream
  - Most downtime caused by support equipment
- **116 hours of DSRP operation with >90% sulfur removal**
- **Guard Bed**
  - 2541 hr bypassing Guard Bed
  - 476 hr using Guard Bed
  - No detectable difference in WGDS performance

RTI Desulfurization Unit / DSRP at Eastman Plant

WGCU/DSRP
Nexant Preliminary Study

	IGCC Base Case *LTGC + SELEXOL + CLAUS + SCOT*	IGCC RTI Case *RTI WGCU/DSRP*
Coal Feed, STPD (AR)	5,763	5,763
Electric Power, MW	554	618
Total Plant Aux. Consumption, MW	137	126
HHV, %	35.8	39.9
Total Installed Cost (TPC), $MM (2006)	1,127.7	1,096.8
Installed Cost, $/Net kW	2,036	1,775

Integrated Warm Gas Multicontaminant Cleanup

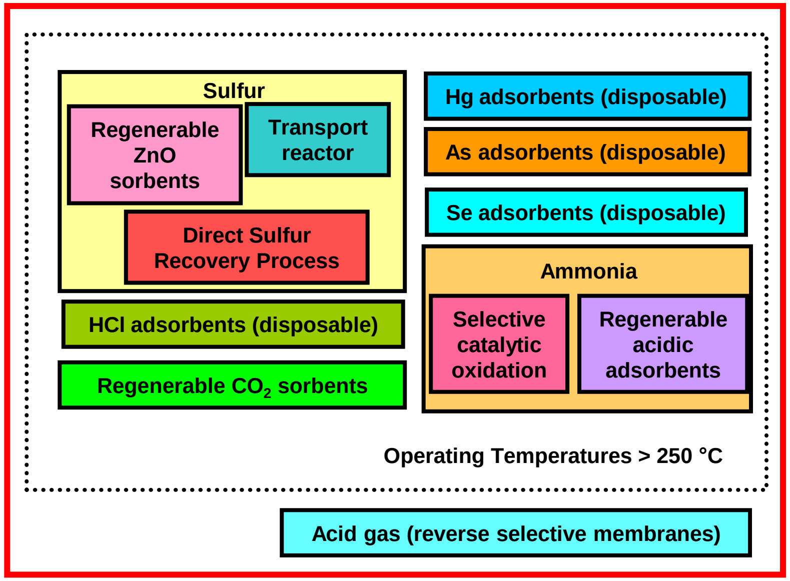
RTI International

Goal:

Support the development of a warm multi-contaminant syngas cleaning system for operation between 300-700 °F and up to 1,200 psig that will clean coal-derived syngas to near-zero levels

Accomplishments:

- Developed and validated lab-scale testing systems to test sorbent exposure using simulated syngas containing S, Hg, arsine (AsH_3), hydrogen selenide (H_2Se), and NH_3 at temperatures >392ºF
- Performed analysis for trace metals present in sorbent materials generated during exposure to real coal-derived syngas
- Screened CO_2 sorbent materials; several novel magnesium oxide (MgO) preparation techniques were used, resulting in sorbents that showed CO_2 capacity of 40 to 60 wt%.



RTI's Warm Syngas Cleaning Technology Platform

Benefits:

Warm gas cleanup technologies (based on the RTI sulfur removal process) can improve the overall efficiency of an IGCC power plant by about 2.3 percentage points and reduce the cost of electricity by 4 percent

Integrated Multicontaminant Removal Process

Gas Technology Institute

Goal:

Develop a multi-contaminant removal process in which H_2S, NH_3, HCl, and heavy metals, including Hg, As, Se, and Cd, are removed to specified levels in a single/integrated process step in the temperature range of 285 - 300°F

GTI's Bench-Scal Unit

Status:

- Complete preliminary Aspen process simulation modeling.
- A CrystaSulf candidate catalyst was successfully tested for 100 hours. These tests showed optimum regeneration may occur at 570°F
- The Bench-Scale Unit construction is completed and the unit is in commissioning.

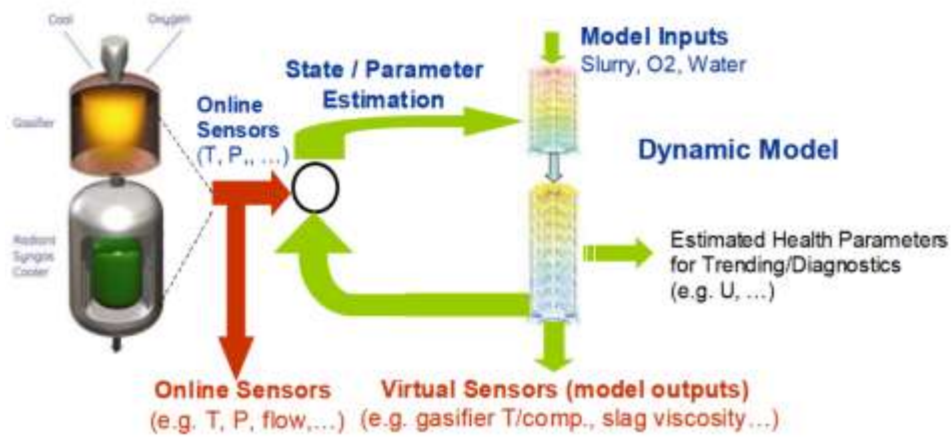
Benefits:

An economic evaluation shows 40% reduction in capital and operating cost for the proposed scheme compared with conventional approaches.

Development of Model Based Controls
for GE's Gasifier and Syngas Cooler

Goal:
Develop and evaluate an advanced sensing and control solution for increased operational flexibility of the core gasification section (e.g., gasifier and syngas cooler), including flexible operation with feedstock changes, throughput changes (to enable load following), and reduced start-up time

Accomplishments:
- Developed and simulated advanced MPC solution using ideal sensors
- Performed validation and comparison of MPC solution from ideal sensors to actual TECO gasifier sensor data
- Updated gasification model and sensing system design



Benefits:
Support for gasification commercialization due to increased plant reliability and performance through advanced system control utilizing a predictive control model

Congressionally Directed Projects

Air Products and Chemicals, Inc.

- Investigate integration of reaction-driven ITM technology with gasification technologies that process heavy feed stocks (i.e. coal, biomass, and petcoke)
- Evaluate the estimated capital and operating costs and the level of carbon dioxide emissions of the integrated facility versus those of a base case

New Mexico State University
Arrowhead Center to Promote Prosperity and Public Welfare

- Conduct research analyzing the relationships between the fossil-fuel energy sector and economic development issues in New Mexico
- Actively engage stakeholders in the research process
- Provide a timely, focused economic research product on the inter-relationships between fossil-fuel energy, the economy, and the environment, especially applicable to the State of New Mexico

Related Technology Development in the *Advanced Research (AR) Program*

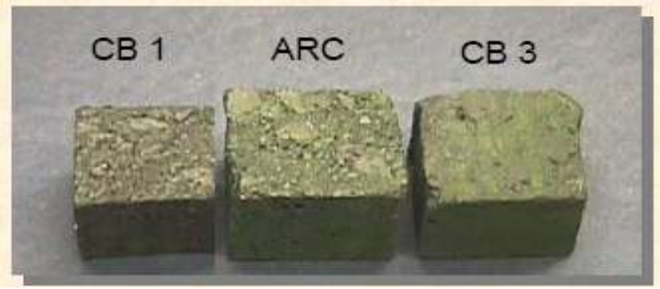
Approximate Research Funding Over Next Three Years: $13,000,000

Sensors and Controls

- Fiber optic sensors for harsh environments
  - Sapphire based materials for temperature sensor
  - Silica based materials for gas sensing (H_2 & CO)
- Model Based Controls & Integrated Sensing for entrained flow gasifiers
- Integration of advanced control into development of Chemical Looping (CL) Processes
- Wireless-Passive & Embedded sensors for temperature & refractory
- Laser Based Detection of temperature & gases for low attenuation harsh environments

Materials

- Refractory Materials (Low Chromium)
- Computational and Experimental Design of alloys and coatings for corrosion resistance

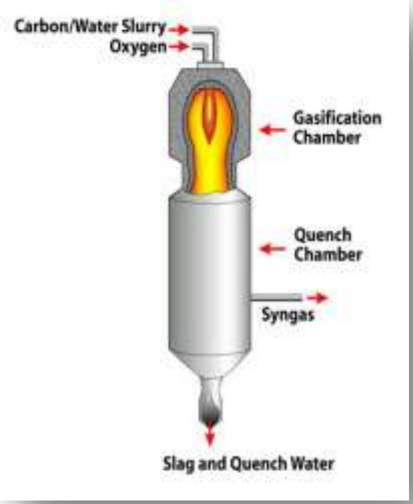


Computational Energy Technology

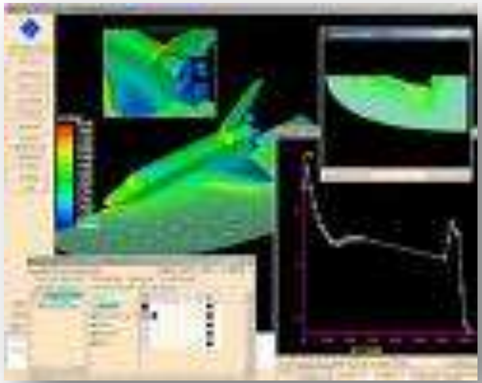
- Multiphase Flow, Reduced Order Modeling, and Process Simulation for IGCC & CL

NETL Office of Research & Development

Gasification Projects



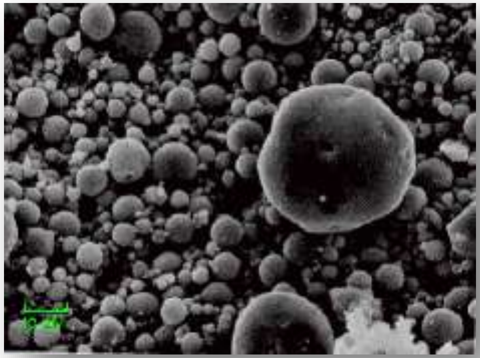
- **Co-gasification Kinetics and Product Characterization**
  - Design and modify gasification unit for steady state operation at entrained gasification conditions
- **Biomass/Coal Prep. for Gasification Systems**
  - Prepare topical report on biomass feedstock types for gasification systems
  - Chemical characterization of biomass materials
- **IGCC Dynamic Simulator Research & Training Center**
  - Design IGCC control system and human machine interface (HMI)
  - Validate dynamic model
  - Perform factory acceptance testing

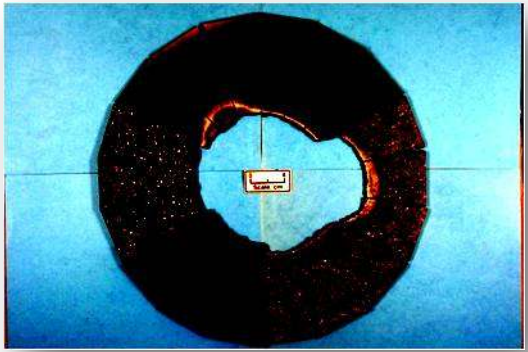


NETL Office of Research & Development

Gasification Projects (continued)

- **Control of Carbon Feedstock Slag and Its Impact on Gasifier Operation**
  - Review performance/predictive ability of slag model for mixed feedstocks
  - Rotary slag drum tests of no and low chrome oxide refractory materials
  - Fabricate mixed feedstock slag compositions for high temperature evaluation
- **Slagging Gasifier Model Development**
  - Model coal and petcoke partitioning, validate using commercial experience
  - Develop user defined CFD function and verify for fly ash wall interaction
- **Fundamentals of Gasification Kinetics: Development of Carbonaceous Chemistry for Computational Modeling (C_3M)**
  - Develop GUI and CFD-C_3M interface and slag model
- **Transport Desulfurizer Modeling**
  - Simulate gas cleaning absorption/regeneration reactors for a 50 MWe plant





IGCC Dynamic Simulator & Research Center

Office of Research and Development

- **Mission: "IGCC with CO_2 capture" research, demonstration, education, and training**
- **Objective: Full-scope, high-fidelity, real-time dynamic simulator**
  - Start-ups, shutdowns, and load changes
  - Normal, abnormal and emergency operating conditions
  - Full DCS emulation and control strategy analysis
  - Instructor station, scenarios, trending, snapshots, etc.
- **Location**
  - Flagship research center at NETL
  - Training and education center at WVU's National Research Center for Coal & Energy (NRCCE)
- **Operation**
  - NETL Institute for Advanced Energy Solutions (IAES)
  - Collaboratory for Process & Dynamic Systems Research
- **NETL Collaboration Partners**
  - Invensys Process Systems/West Virginia University
  - Fossil Consulting Services, Enginomix, EPRI/CoalFleet
- **Current Status**
  - Development phase initiated in Q1FY2009
  - Establish the Dynamic Simulator Research & Training Center and Deployment of the IGCC Dynamic Simulator in FY2010

Process Training Simulator (Source: Invensys Process Systems)

Planned Configuration for NETL IGCC Dynamic Simulator

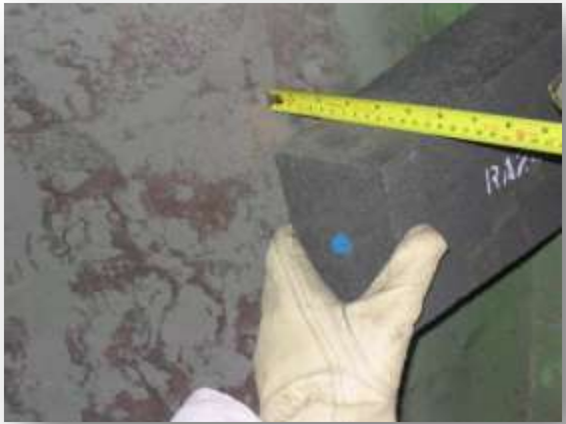
Advanced Refractories for Gasifiers

Office of Research and Development

Enhancing reliability, performance, and on-line availability of gasification systems

Project Objectives:

- Develop refractories with improved performance
  longer and predictable service life
- Develop refractories that are environmentally friendly and cost effective
  low/no chrome, minimize Cr+6 formation
- Develop refractories with carbon feedstock flexibility
  - model gasifier slag (predict chemistry, viscosity, and phases formed)
  - control slag/refractory interactions and slag viscosity
  - design slag to increase refractory service life
- Develop reliable sensors to accurately monitor gasification temperature



Failed refractory material ←

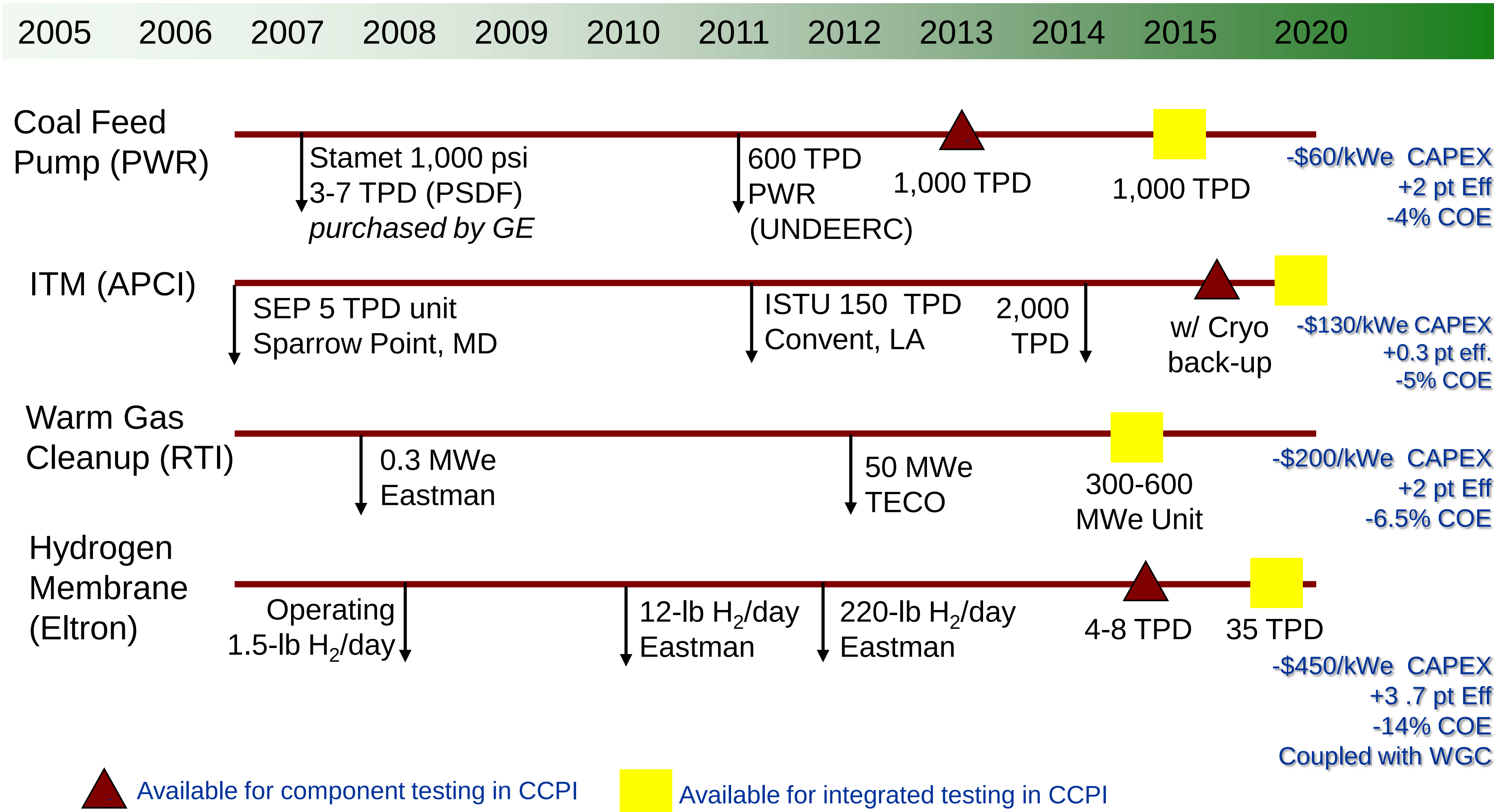
Failed thermocouple →

NETL Office of Systems Analysis & Planning *Gasification Projects*

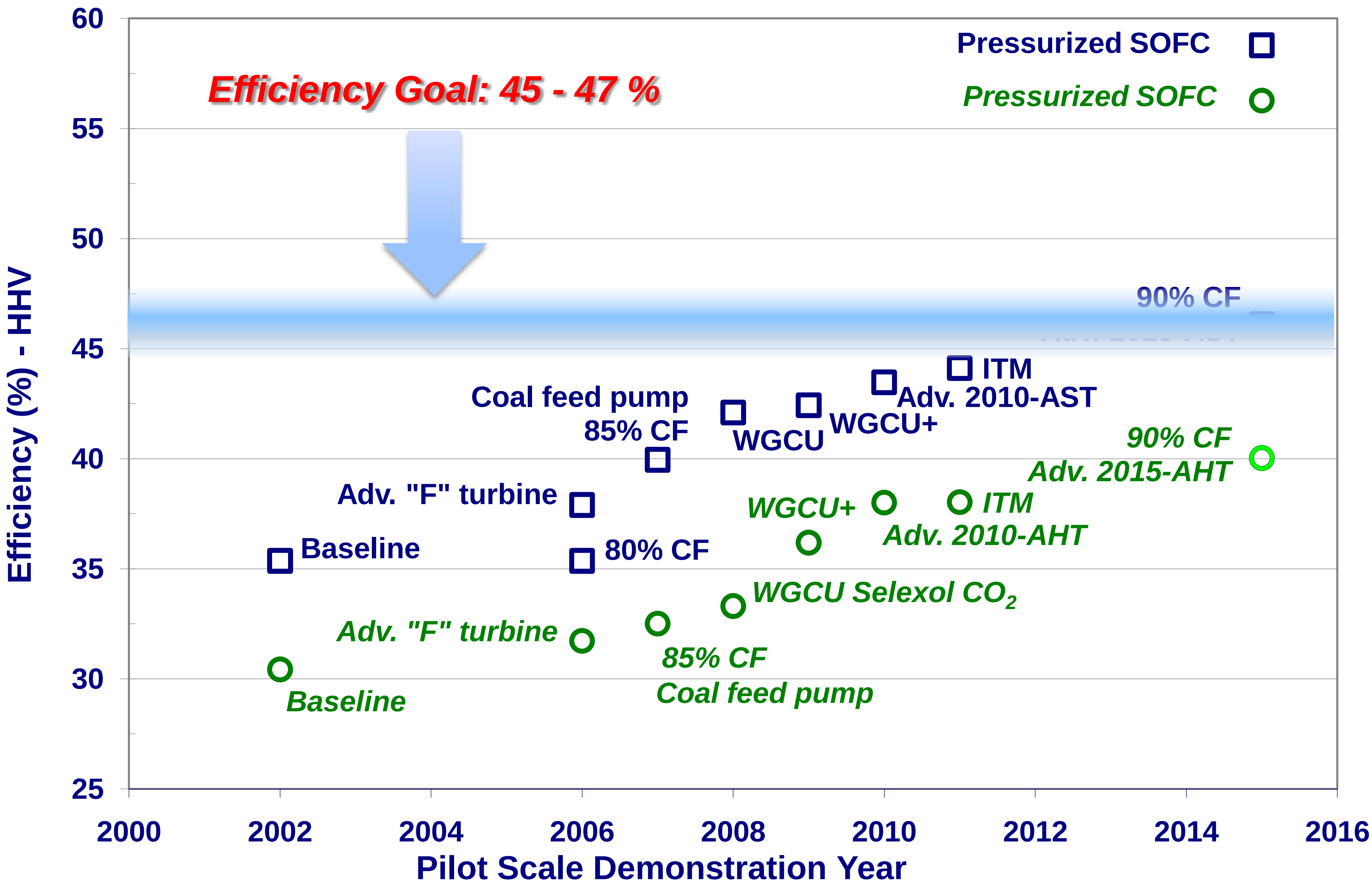
- **Major Reports**
  - A Pathway Study Focused on Carbon Capture Advanced Power Systems R&D Using Bituminous Coal – Volume 2 (in progress)
  - Cost and Performance Baseline for Fossil Energy Plants – Low Rank Coal (in progress)
  - GHG Reduction in the Power Industry Using Domestic Coal and Biomass (in progress)
  - Cost and Performance Baseline for Fossil Energy Plants – Coal to Substitute Natural Gas (in progress)
  - Life Cycle Analysis of Energy Conversion Systems (2009)
- **Technology Screening Analyses**
  - Assessment of Iron-Based Chemical Looping for Pre-Combustion Carbon Capture in an IGCC System (OSU)
  - Assessment of UC-Riverside Hydrogasification for Production of F-T Fuels, Electric Power, and SNG (Viresco Energy)

Technology Roadmap Timeline

Gasification Program
Technology Commercialization Timeline

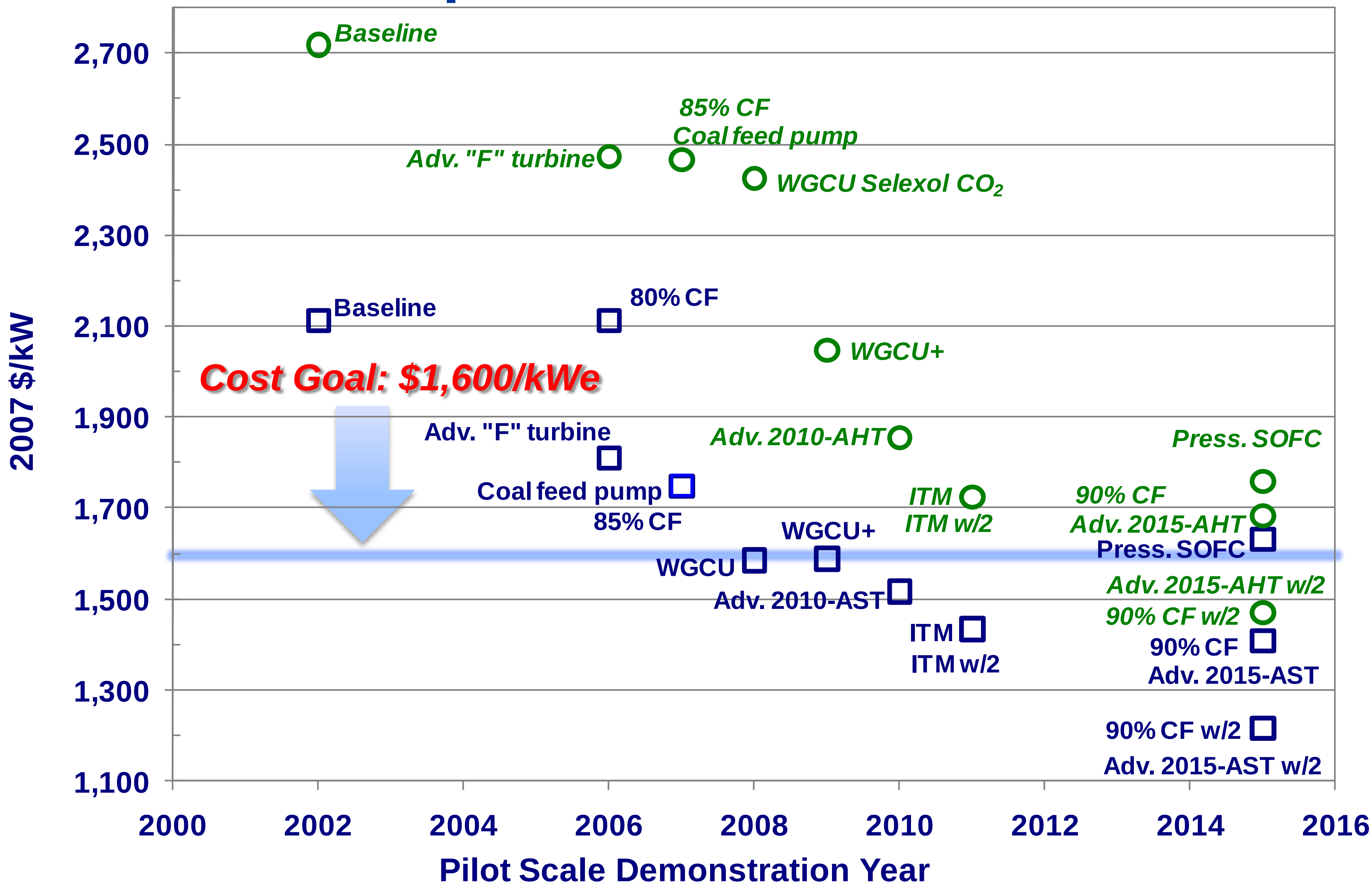


Efficiency Timeline



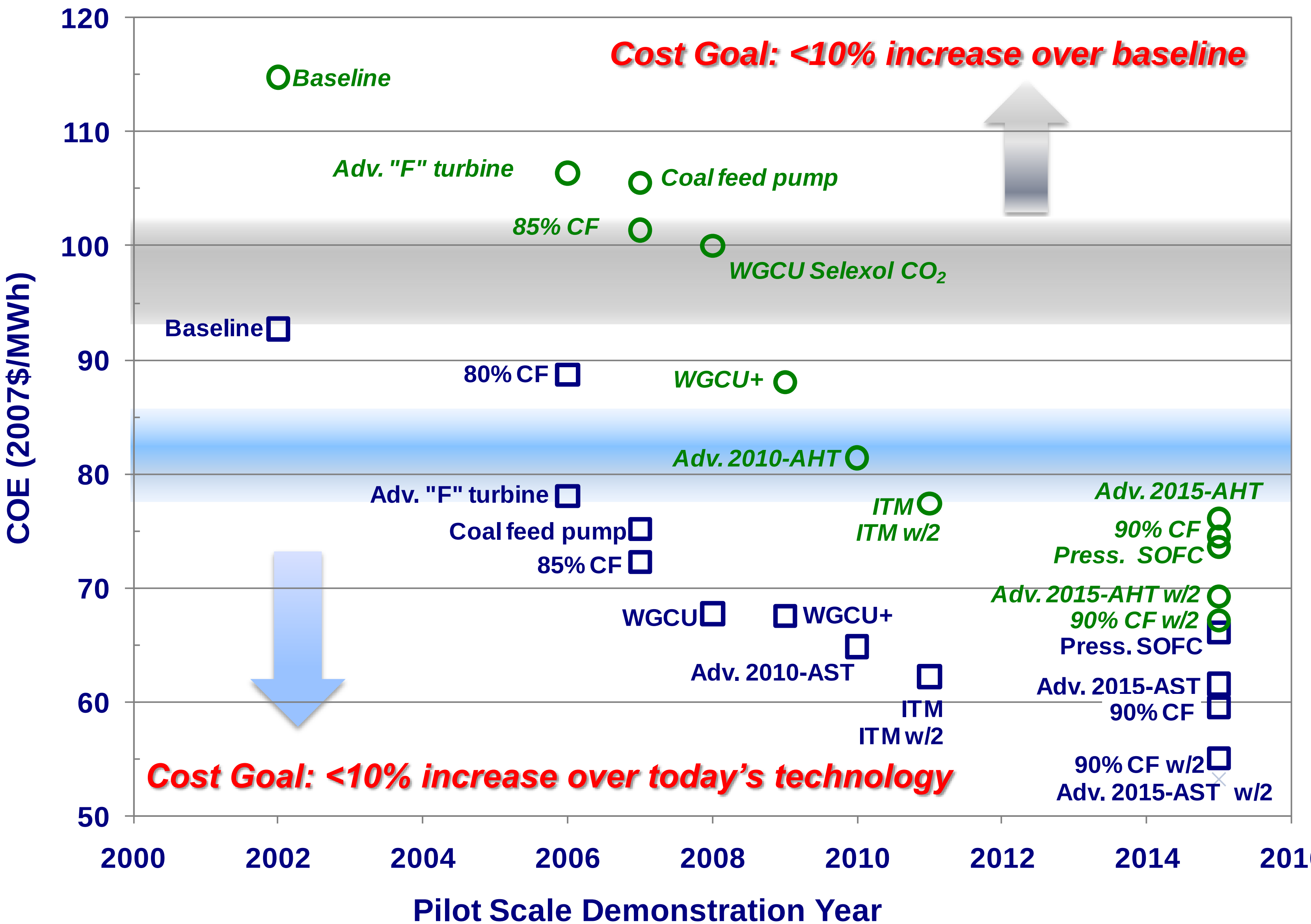
□ = without carbon capture ○ = *with carbon capture*

Capital Cost Timeline



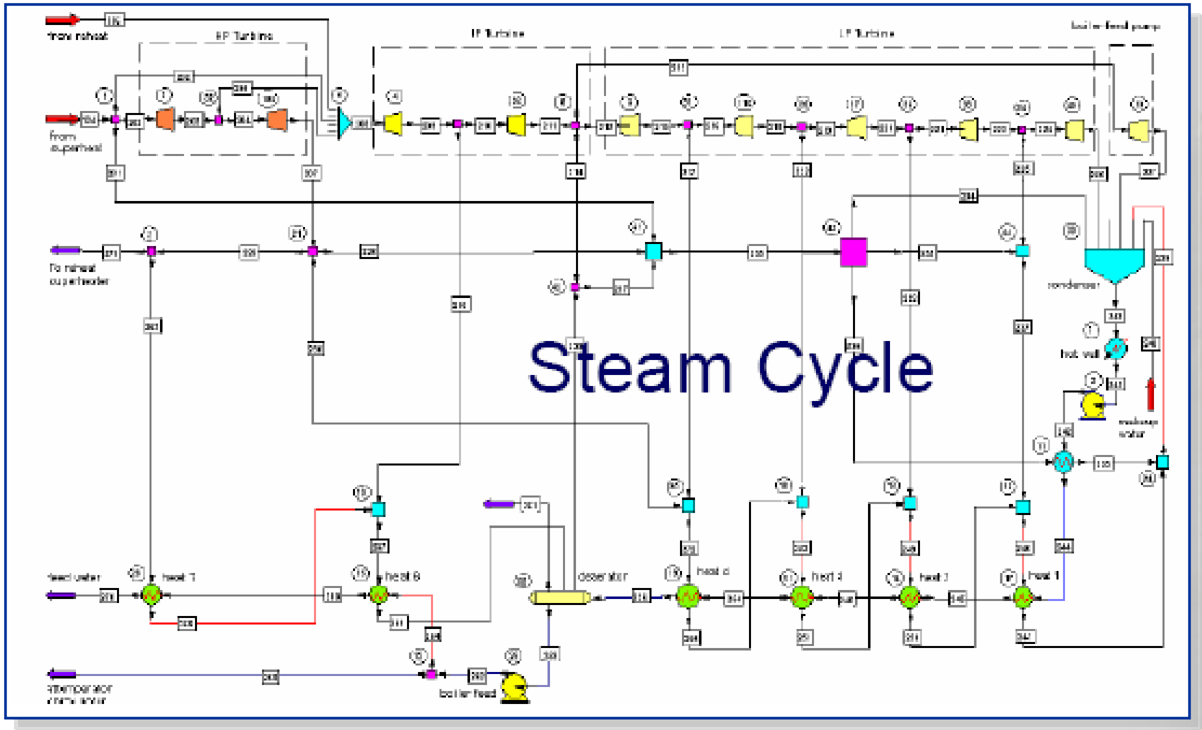
□ = without carbon capture ○ = *with carbon capture*

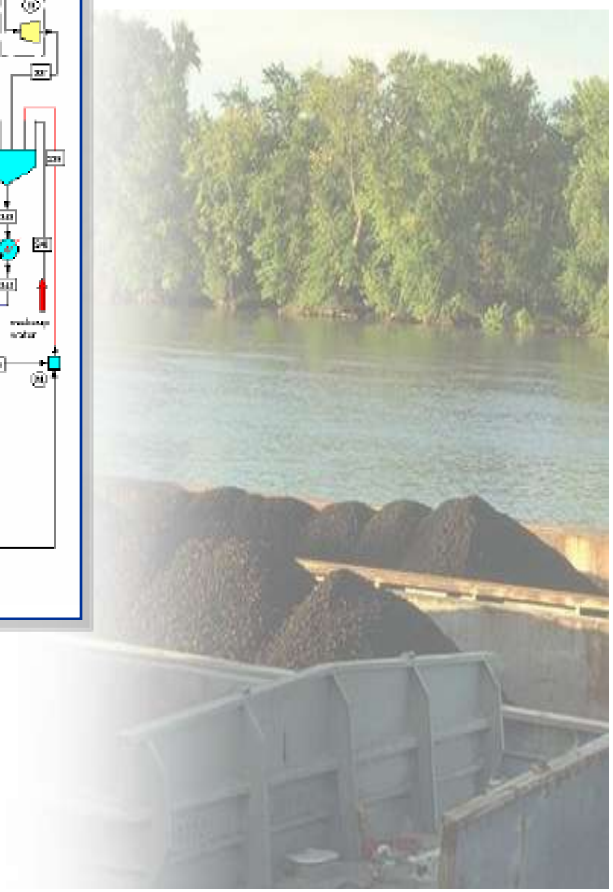
COE Timeline



□ = without carbon capture ○ = *with carbon capture*

Baseline Analysis





Study Matrix

Plant Type	ST Cond. (psig/°F/°F)	GT	Gasifier/ Boiler	Acid Gas Removal/ CO_2 Separation / Sulfur Recovery	CO_2 Cap
IGCC	1800/1050/1050 (non-CO_2 capture cases) 1800/1000/1000 (CO_2 capture cases)	F Class	GE	Selexol / - / Claus	
				Selexol / Selexol / Claus	90%
			CoP E-Gas	MDEA / - / Claus	
				Selexol / Selexol / Claus	88%[1]
			Shell	Sulfinol-M / - / Claus	
				Selexol / Selexol / Claus	90%
PC	2400/1050/1050		Subcritical	Wet FGD / - / Gypsum	
				Wet FGD / Econamine / Gypsum	90%
	3500/1100/1100		Supercritical	Wet FGD / - / Gypsum	
				Wet FGD / Econamine / Gypsum	90%
NGCC	2400/1050/950	F Class	HRSG		
				- / Econamine / -	90%

[1] CO_2 capture is limited to 88% by syngas CH_4 content

GEE – GE Energy
CoP – Conoco Phillips

Design Basis: Coal Type

Illinois #6 Coal Ultimate Analysis (weight %)

	As Rec'd	Dry
Moisture	11.12	0
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen (by difference)	6.88	7.75
	100.0	100.0
HHV (Btu/lb)	11,666	13,126

Environmental Targets

Pollutant	IGCC[1]	PC[2]	NGCC[3]
SO_2	0.0128 lb/MMBtu	0.085 lb/MMBtu	< 0.6 gr S /100 scf
NOx	15 ppmv (dry) @ 15% O_2	0.07 lb/MMBtu	2.5 ppmv @ 15% O_2
PM	0.0071 lb/MMBtu	0.017 lb/MMBtu	Negligible
Hg	> 90% capture	1.14 lb/TBtu	Negligible

[1] Based on EPRI's CoalFleet User Design Basis Specification for Coal-Based IGCC Power Plants
[2] Based on BACT analysis, exceeding new NSPS requirements
[3] Based on EPA pipeline natural gas specification and 40 CFR Part 60, Subpart KKKK

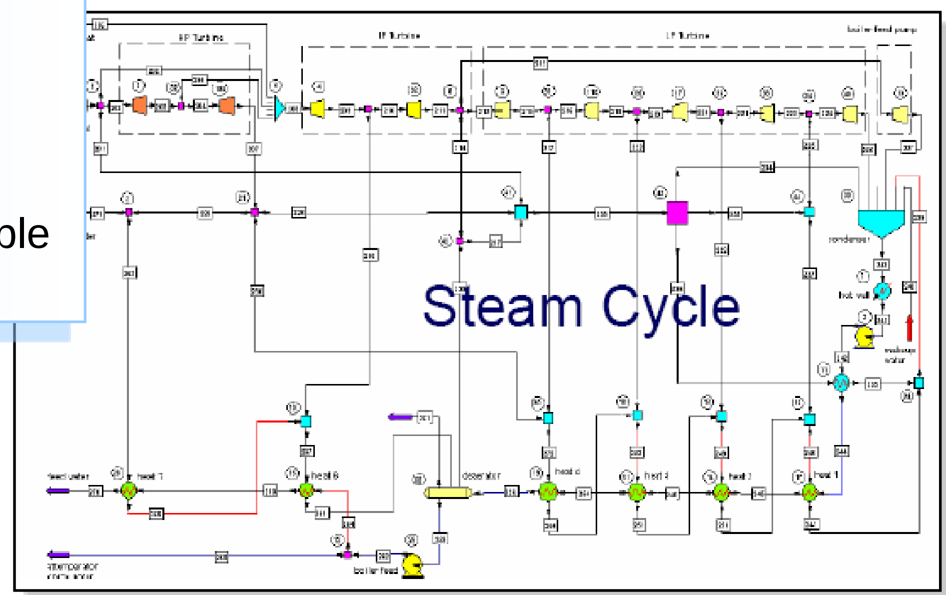
Technical Approach

1. Extensive Process Simulation (ASPEN)

- All major chemical processes and equipment are simulated
- Detailed mass and energy balances
- Performance calculations (auxiliary power, gross/net power output)

2. Cost Estimation

- Inputs from process simulation (Flow Rates/Gas Composition/ Pressure/Temperature)
- Sources
  - Parsons
  - Vendor sources where available
- Follow DOE Analysis Guidelines



Study Assumptions

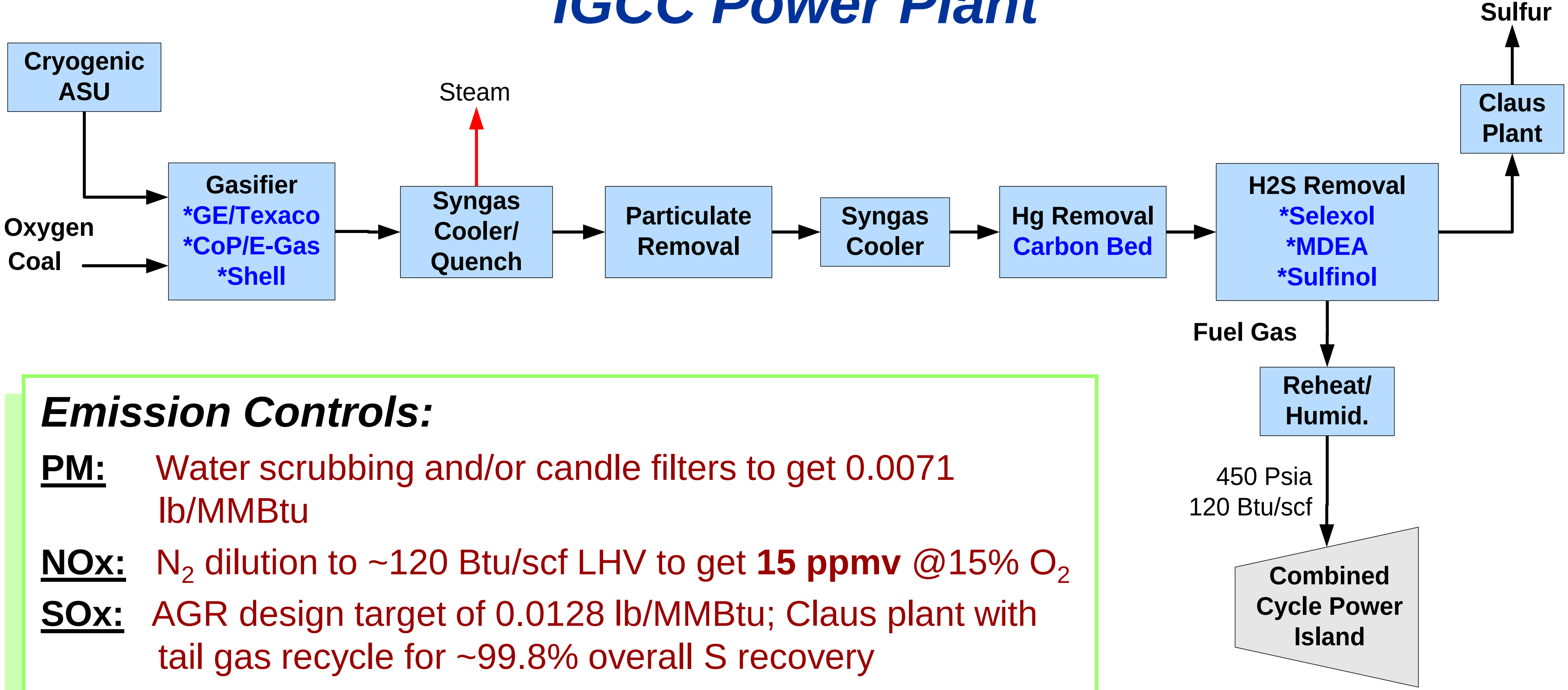
- **Capacity Factor = Availability**
  - IGCC capacity factor = 80% w/ no spare gasifier
  - PC and NGCC capacity factor = 85%
- **GE gasifier operated in radiant/quench mode**
- **Shell gasifier with CO_2 capture used water injection for cooling (instead of syngas recycle)**
- **Nitrogen dilution was used to the maximum extent possible in all IGCC cases and syngas humidification/steam injection were used only if necessary to achieve approximately 120 Btu/scf syngas LHV**
- **In CO_2 capture cases, CO_2 was compressed to 2200 psig, transported 50 miles, sequestered in a saline formation at a depth of 4,055 feet and monitored for 80 years**
- **CO_2 transport, storage and monitoring (TS&M) costs were included in the levelized cost of electricity (COE)**

IGCC Power Plant

Current State-of-the-Art

Current Technology

IGCC Power Plant



Emission Controls:

<u>PM:</u> Water scrubbing and/or candle filters to get 0.0071 lb/MMBtu

<u>NOx:</u> N_2 dilution to ~120 Btu/scf LHV to get **15 ppmv** @15% O_2

<u>SOx:</u> AGR design target of 0.0128 lb/MMBtu; Claus plant with tail gas recycle for ~99.8% overall S recovery

<u>Hg:</u> Activated carbon beds for ~95% removal

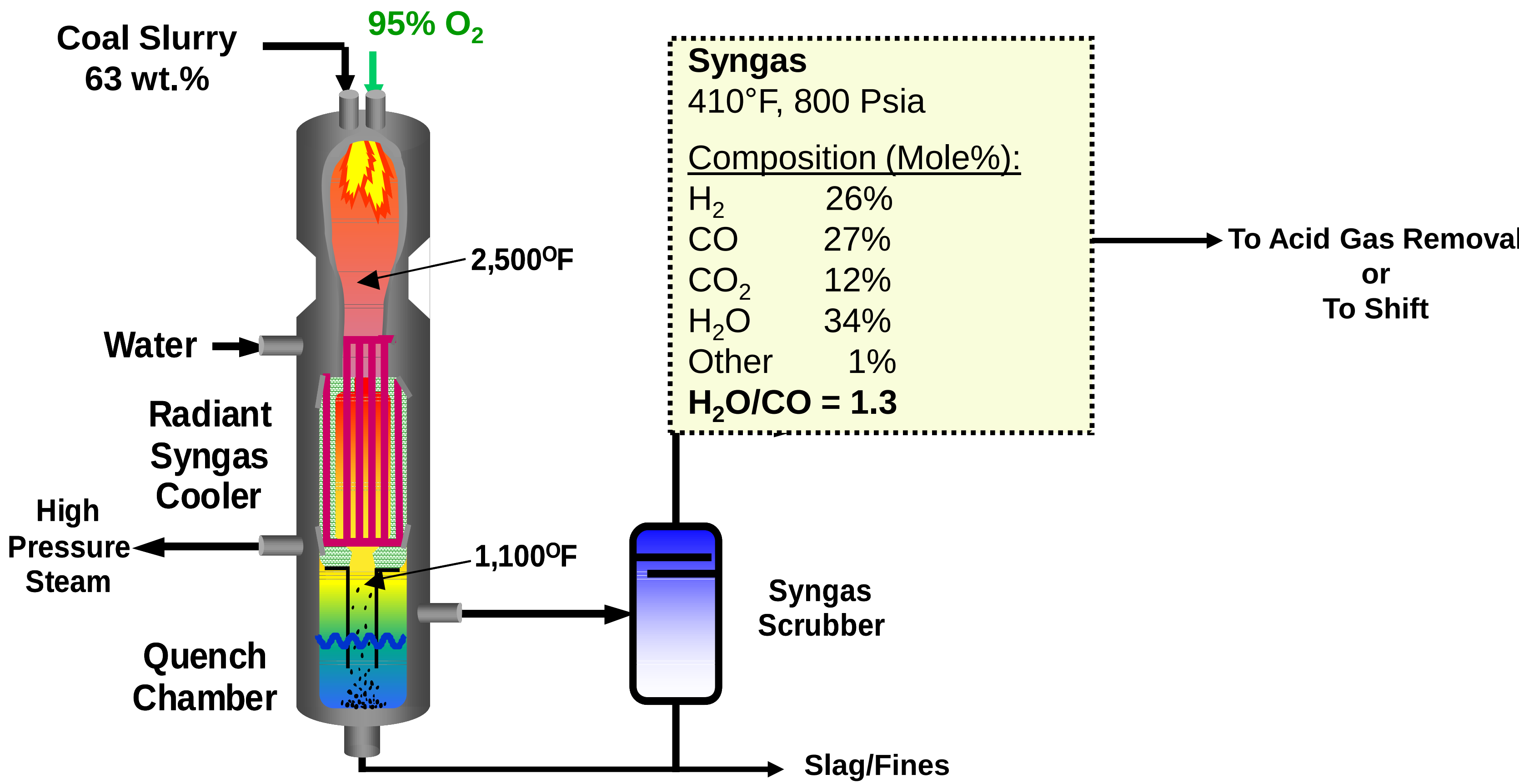
<u>Advanced F-Class CC Turbine:</u> 232 MWe

<u>Steam Conditions:</u>

1800 psig/1050°F/1050°F (non-CO_2 capture cases)

1800 psig/1000°F/1000°F (CO_2 capture cases)

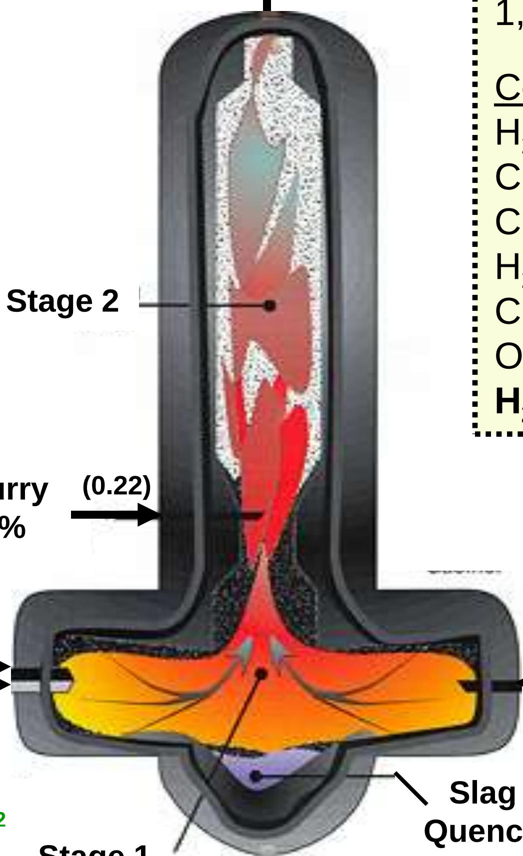
GE Energy Radiant



Design: Pressurized, single-stage, downward firing, entrained flow, slurry feed, oxygen blown, slagging, radiant and quench cooling

Note: All gasification performance data estimated by the project team to be representative of GE gasifier

ConocoPhillips E-Gas™



Syngas
1,700°F, 614 psia

Composition (Mole%):

H_2	26%
CO	37%
CO_2	14%
H_2O	15%
CH_4	4%
Other	4%

H_2O/CO = 0.4

Design: Pressurized, two-stage, upward firing, entrained flow, slurry feed, oxygen blown, slagging, fire-tube boiling syngas cooling, syngas recycle

Note: All gasification performance data estimated by the project team to be representative of an E-Gas gasifier

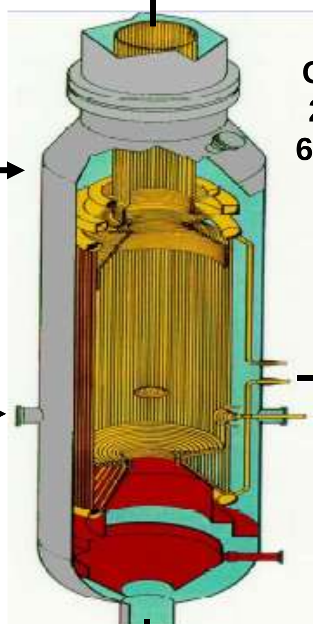
Shell Gasification

HP Steam

Convective Cooler Soot Quench & Scrubber

Syngas Quench[2]

Gasifier
2,700ºF
615 psia



HP Steam

95% O_2

Dry Coal

Slag

650ºF

Design: Pressurized, single-stage, downward firing, entrained flow, dry feed, oxygen blown, convective cooler

Notes:
1. All gasification performance data estimated by the project team to be representative of Shell gasifier.
2. CO_2 capture incorporates full water quench instead of syngas quench.

Syngas
350°F, 600 Psia

Composition (Mole%):

H_2	29%
CO	57%
CO_2	2%
H_2O	4%
Other	8%

H_2O/CO = 0.1

To Acid Gas Removal or To Shift

Source: "The Shell Gasification Process", Uhde, ThyssenKrupp Technologies

IGCC Performance Results

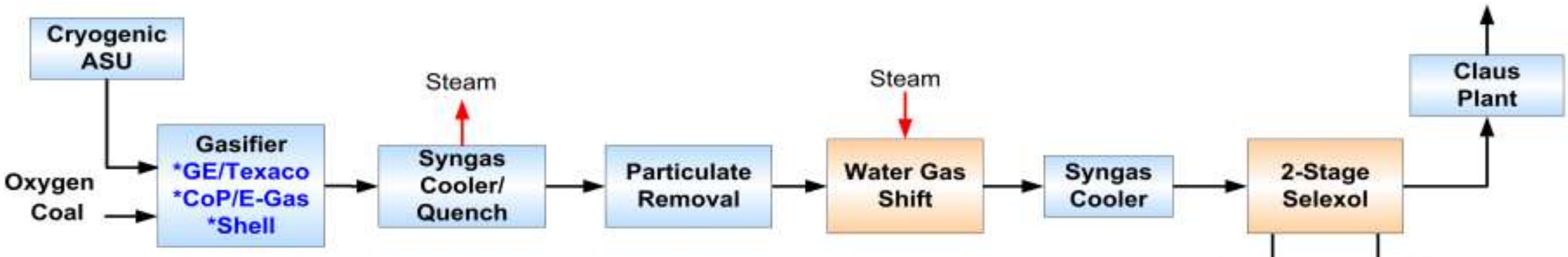
No CO_2 Capture

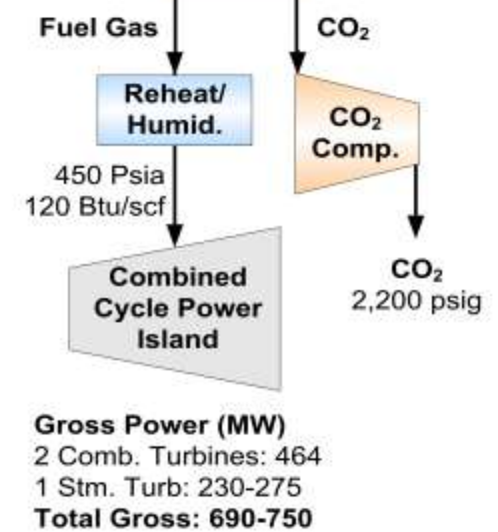
	GE Energy	E-Gas	Shell
Gross Power (MW)	**770**	**742**	**748**
Auxiliary Power (MW)			
Base Plant Load	23	25	21
Air Separation Unit	103	91	90
Gas Cleanup	4	3	1
Total Aux. Power (MW)	130	119	112
Net Power (MW)	640	623	636
Heat Rate (Btu/kWh)	8,922	8,681	8,306
Efficiency (HHV)	**38.2**	**39.3**	**41.1**

IGCC Power Plant With CO_2 Capture

Current Technology

IGCC Power Plant with CO_2 Scrubbing





Emission Controls:

PM: Water scrubbing and/or candle filters to get 0.007 lb/MMBtu

NOx: N_2 dilution to ~120 Btu/scf LHV to get **15 ppmv** @15% O_2

SOx: Selexol AGR removal of sulfur to < **28 ppmv** H_2S in syngas

Claus plant with tail gas recycle for ~99.8% overall S recovery

Hg: Activated carbon beds for ~95% removal

Advanced F-Class CC Turbine: 232 MWe

Steam Conditions: 1800 psig/1000°F/1000°F

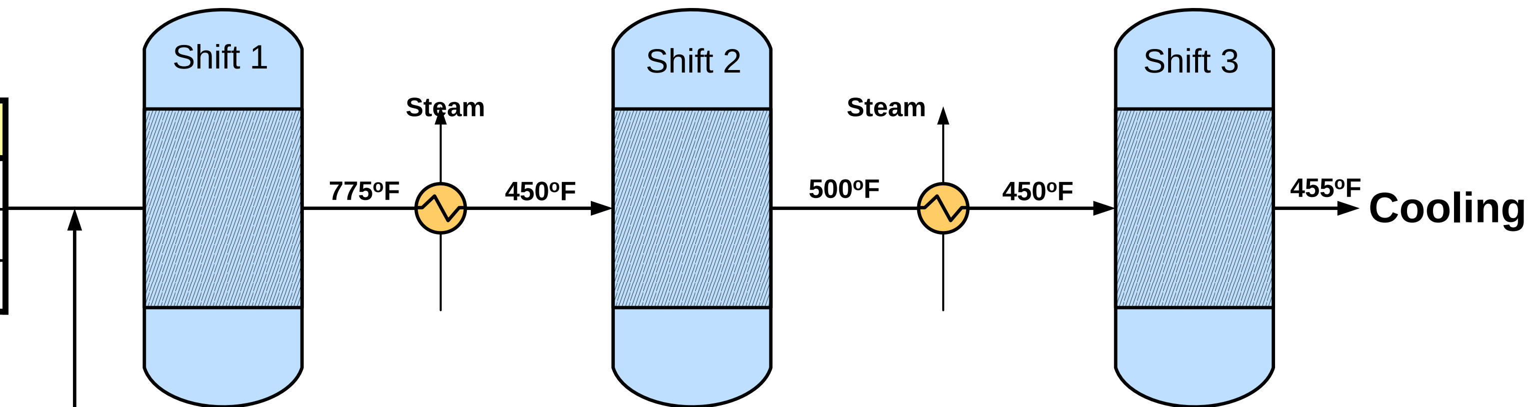
Water-Gas Shift Reactor System

Design:

- Haldor Topsoe SSK Sulfur Tolerant Catalyst
- Up to 97.5% CO Conversion
- 2 stages for GE and Shell, 3 stages for E-Gas
- $H_2O/CO = 2.0$ (Project Assumption)
- Overall ΔP = ~30 psia

H_2O/CO Ratio[1]	
GE	1.3
E-Gas	0.4
Shell	1.5

[1] Prior to shift steam addition



	Relative HP* Steam Flow	Steam Turbine Output (MW)
GE	1.0	275
E-Gas	2.4	230
Shell	0.9	230

*High Pressure Steam

$$H_2O + CO \longleftrightarrow CO_2 + H_2$$

IGCC Performance Results

	GE Energy	
CO_2 Capture	NO	YES
Gross Power (MW)	770	745
Auxiliary Power (MW)		
Base Plant Load	23	23
Air Separation Unit	103	121
Gas Cleanup/CO_2 Capture	4	18
CO_2 Compression	-	27
Total Aux. Power (MW)	130	189
Net Power (MW)	640	556
Heat Rate (Btu/kWh)	8,922	10,505
Efficiency (HHV)	38.2	32.5
Energy Penalty[1]	-	5.7

[1]CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

Steam for Selexol

↑ in ASU air comp. load w/o CT integration

Includes H_2S/CO_2 Removal in Selexol Solvent

IGCC Performance Results

	GE Energy		E-Gas		Shell	
CO_2 Capture	NO	YES	NO	YES	NO	YES
Gross Power (MW)	770	745	742	694	748	693
Auxiliary Power (MW)						
Base Plant Load	23	23	25	26	21	19
Air Separation Unit	103	121	91	109	90	113
Gas Cleanup/CO_2 Capture	4	18	3	15	1	16
CO_2 Compression	-	27	-	26	-	28
Total Aux. Power (MW)	130	189	119	176	112	176
Net Power (MW)	640	556	623	518	636	517
Heat Rate (Btu/kWh)	8,922	10,505	8,681	10,757	8,306	10,674
Efficiency (HHV)	38.2	32.5	39.3	31.7	41.1	32.0
Energy Penalty[1]	-	5.7	-	7.6	-	9.1

[1] CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

IGCC Key Points

IGCC

- HHV efficiency = 38-41% (Supercritical PC is 39.1%)

IGCC with CO_2 Capture

- CO_2 capture reduces efficiency by 6-9 percentage points
- 5-7 percentage points higher than PC with CO_2 capture
- 11-12 percentage points lower than NGCC with CO_2 capture

R&D can increase competitiveness and reduce costs

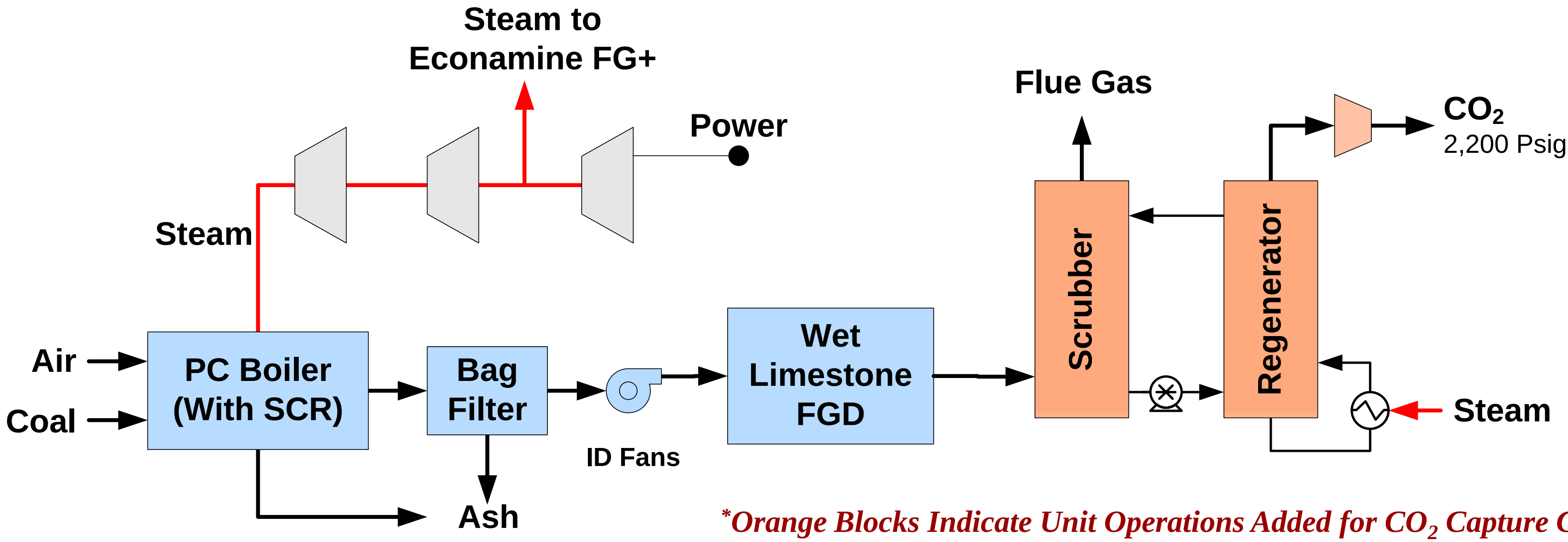
- Reduced ASU cost (membranes)
- Warm gas cleaning for sulfur removal
- Improved gasifier performance
  - carbon conversion, throughput, RAM
- Advanced carbon sorbents and solvents
- High-temperature membranes for shift and CO_2 separation
- Co-sequestration

Comparison to PC and NGCC

Current State-of-the-Art

Current Technology

*Pulverized Coal Power Plant**



**Orange Blocks Indicate Unit Operations Added for CO_2 Capture Case*

PM Control: Baghouse to achieve 0.013 lb/MMBtu (99.8% removal)

SOx Control: FGD to achieve 0.085 lb/MMBtu (98% removal)

NOx Control: LNB + OFA + SCR to maintain 0.07 lb/MMBtu

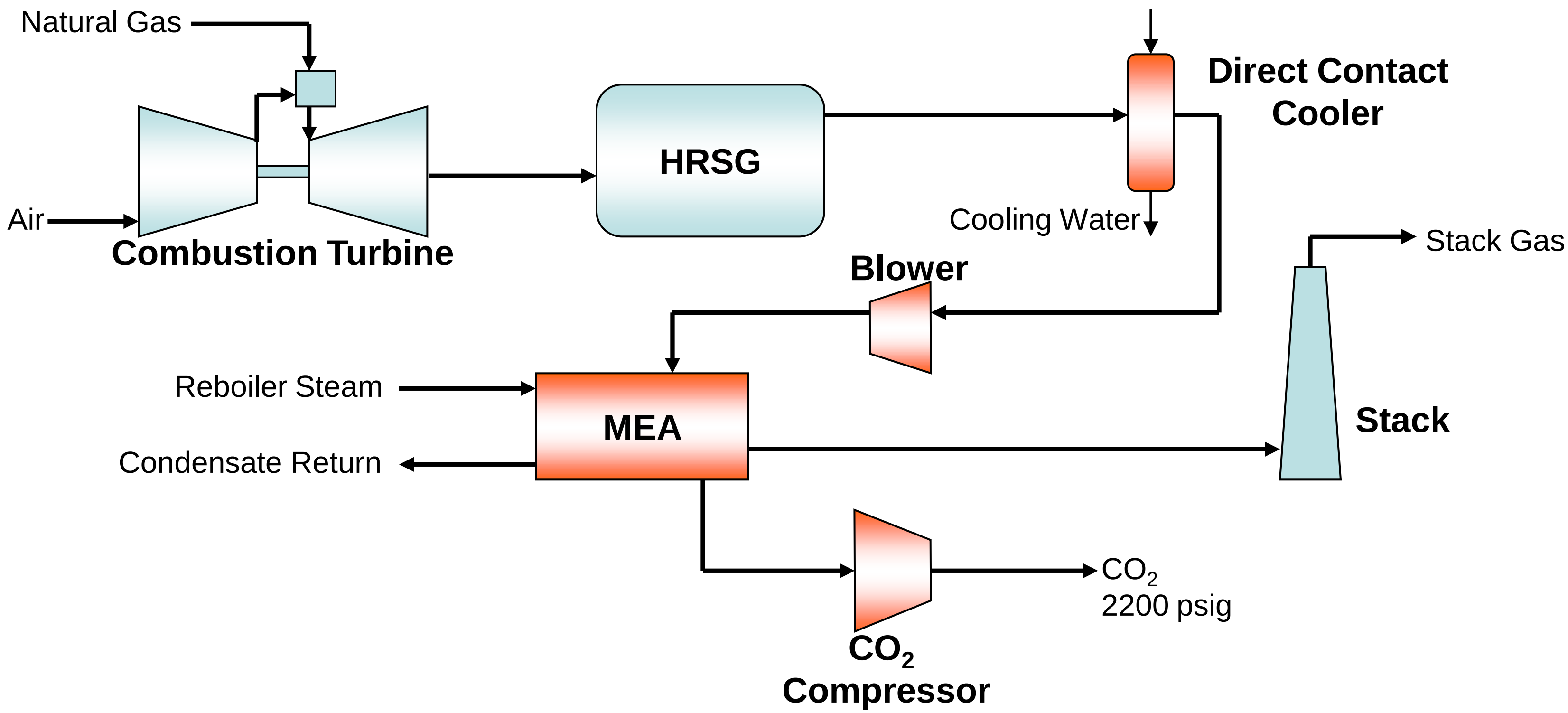
Mercury Control: Co-benefit capture ~90% removal

Steam Conditions (Sub): 2400 psig/1050°F/1050°F

Steam Conditions (SC): 3500 psig/1100°F/1100°F

Current Technology

*Natural Gas Combined Cycle**



**Orange Blocks Indicate Unit Operations Added for CO_2 Capture Case*

NOx Control: LNB + SCR to maintain 2.5 ppmvd @ 15% O_2

Steam Conditions: 2400 psig/1050°F/950°F

PC and NGCC Performance Results

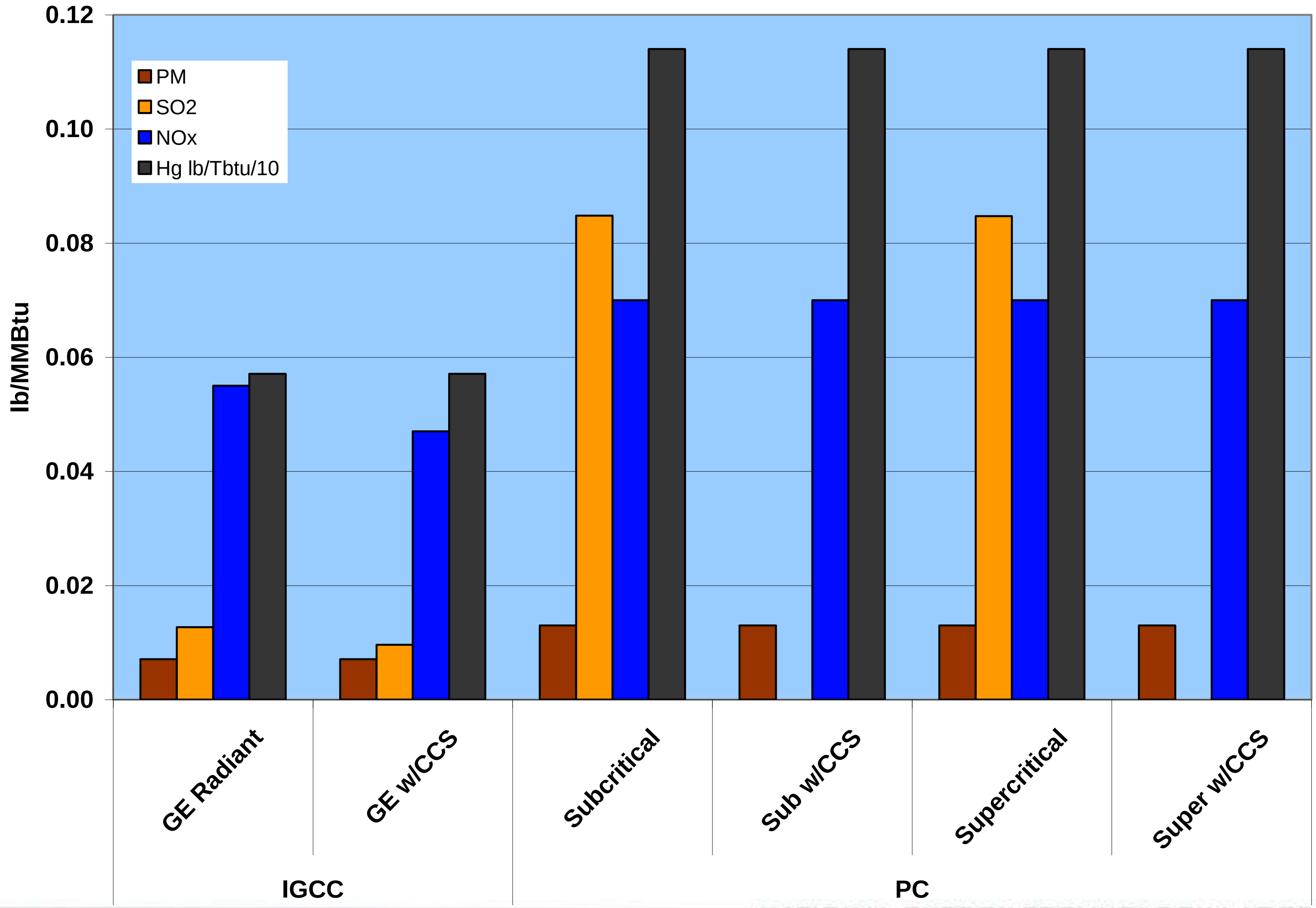
	Subcritical		Supercritical		NGCC	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Gross Power (MW)	**583**	**680**	**580**	**663**	**570**	**520**
Base Plant Load	29	48	26	43	10	13
Gas Cleanup/CO_2 Capture	4	30	4	27	0	10
CO_2 Compression	-	52	-	47	0	15
Total Aux. Power (MW)	**33**	**130**	**30**	**117**	**10**	**38**
Net Power (MW)	550	550	550	546	560	482
Heat Rate (Btu/kWh)	9,276	13,724	8,721	12,534	6,720	7,813
Efficiency (HHV)	**36.8**	**24.9**	**39.1**	**27.2**	**50.8**	**43.7**
Energy Penalty[1]	**-**	**11.9**	**-**	**11.9**	**-**	**7.1**

[1] CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

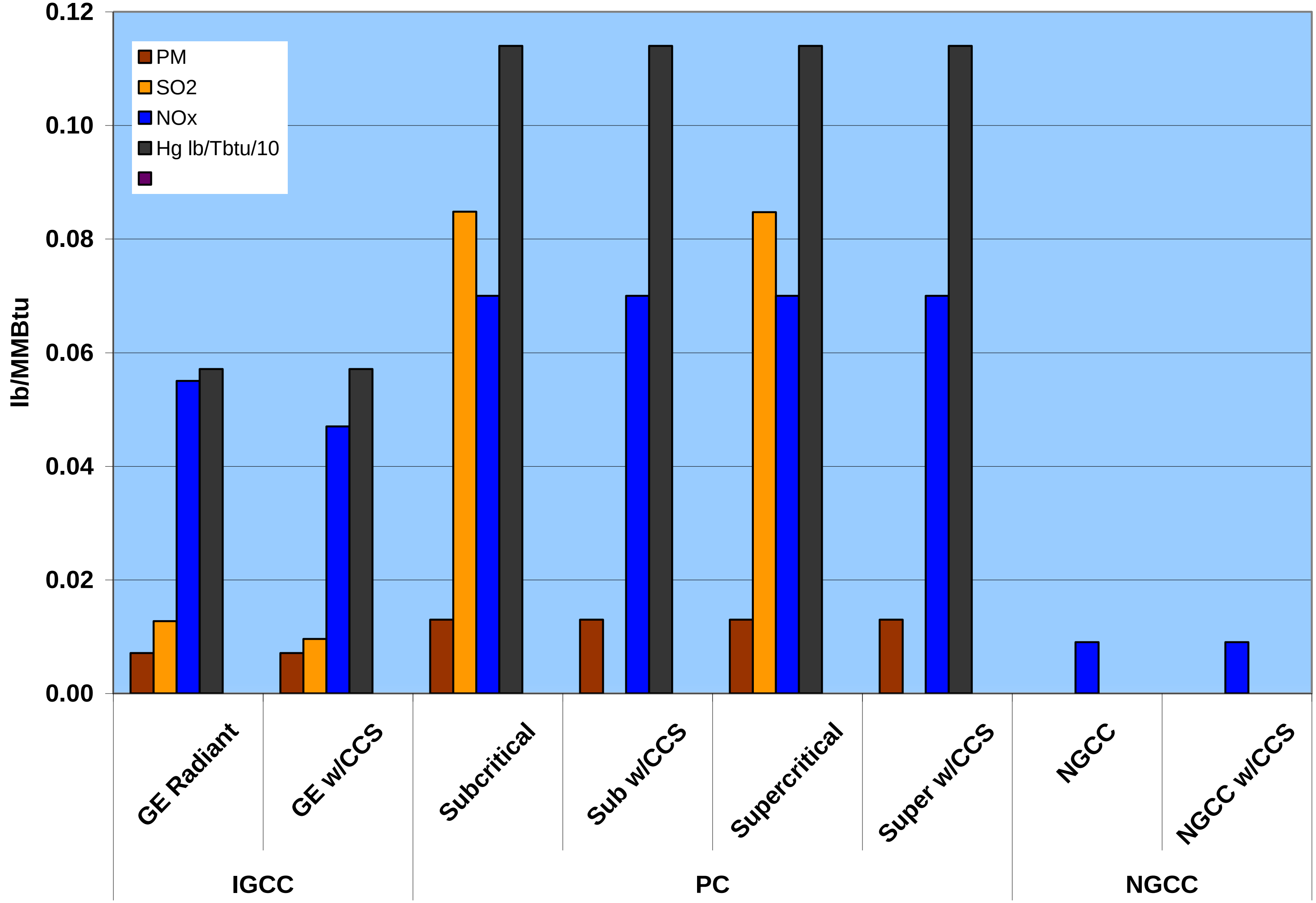
Environmental Performance Comparison

IGCC, PC and NGCC

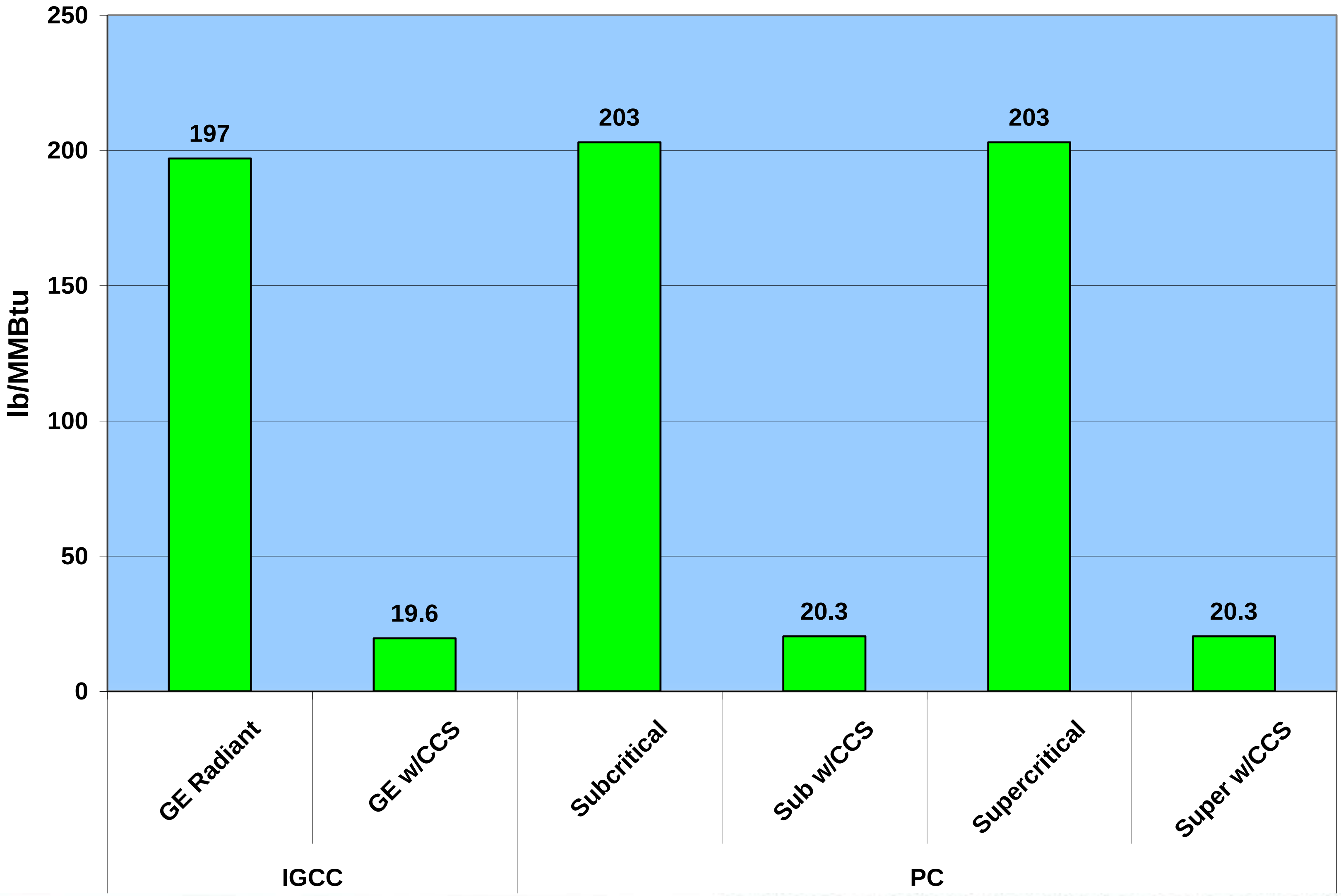
Criteria Pollutant Emissions



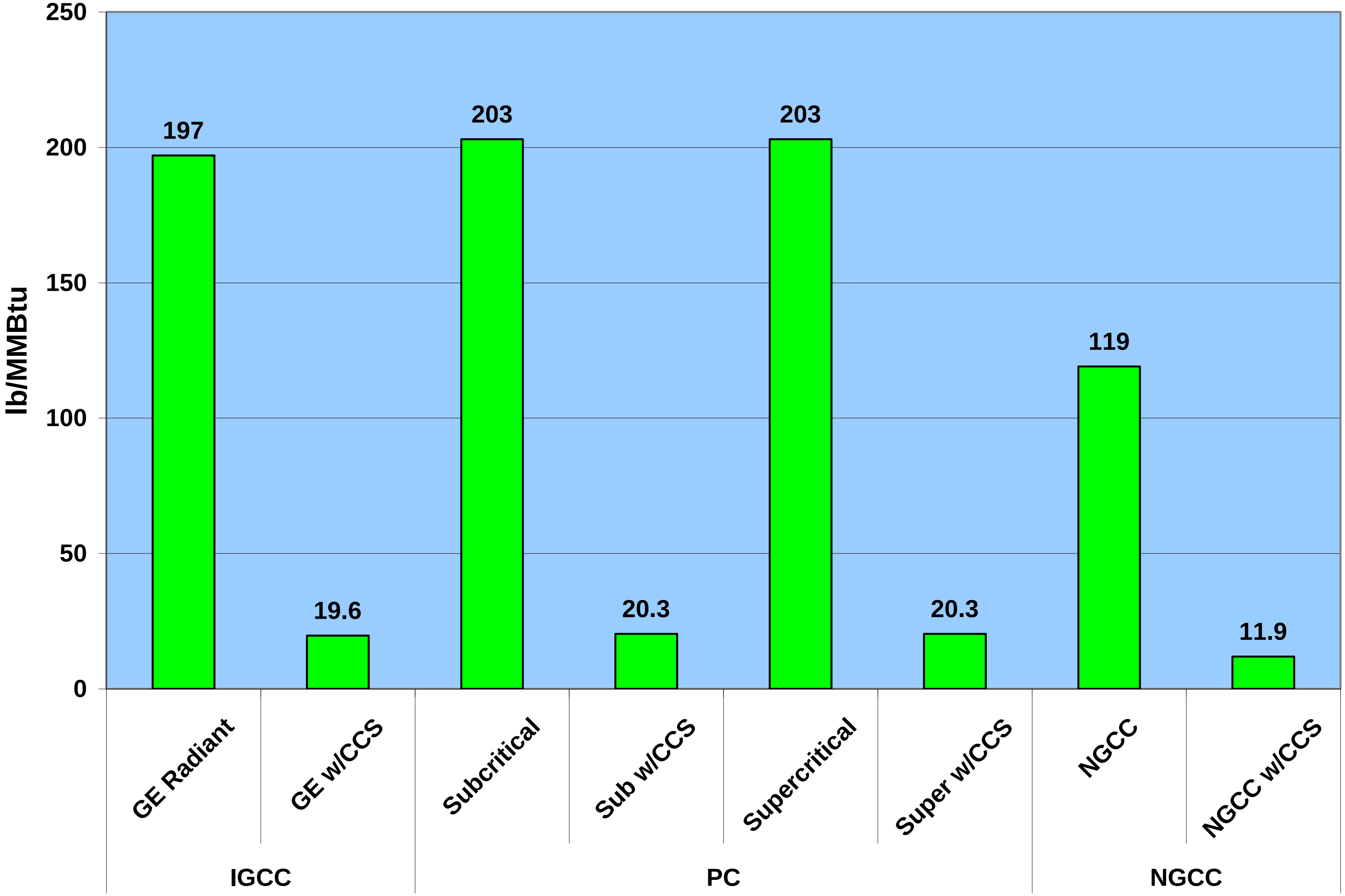
Criteria Pollutant Emissions for All Cases



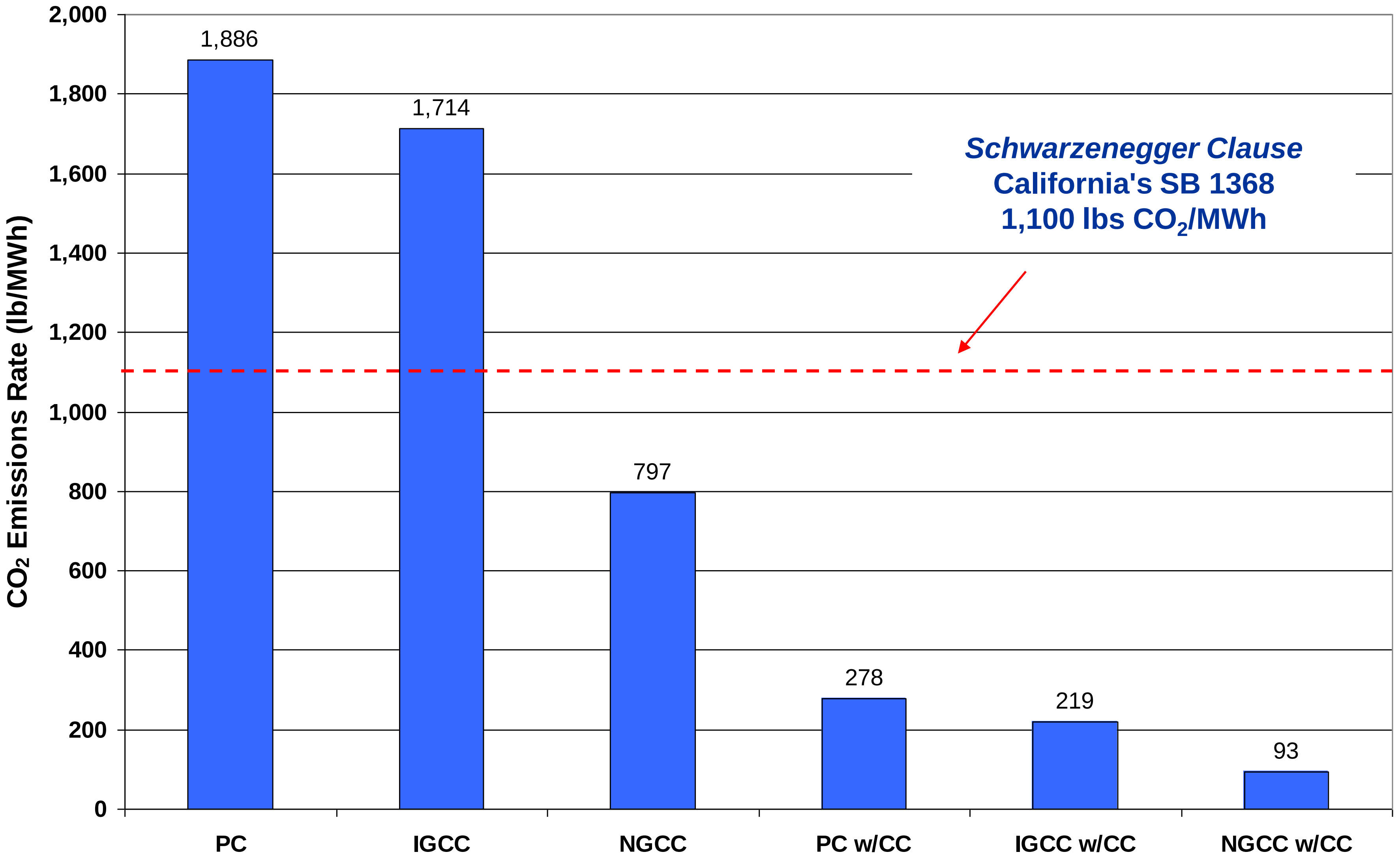
CO_2 Emissions for IGCC & PC



CO_2 Emissions for All Cases



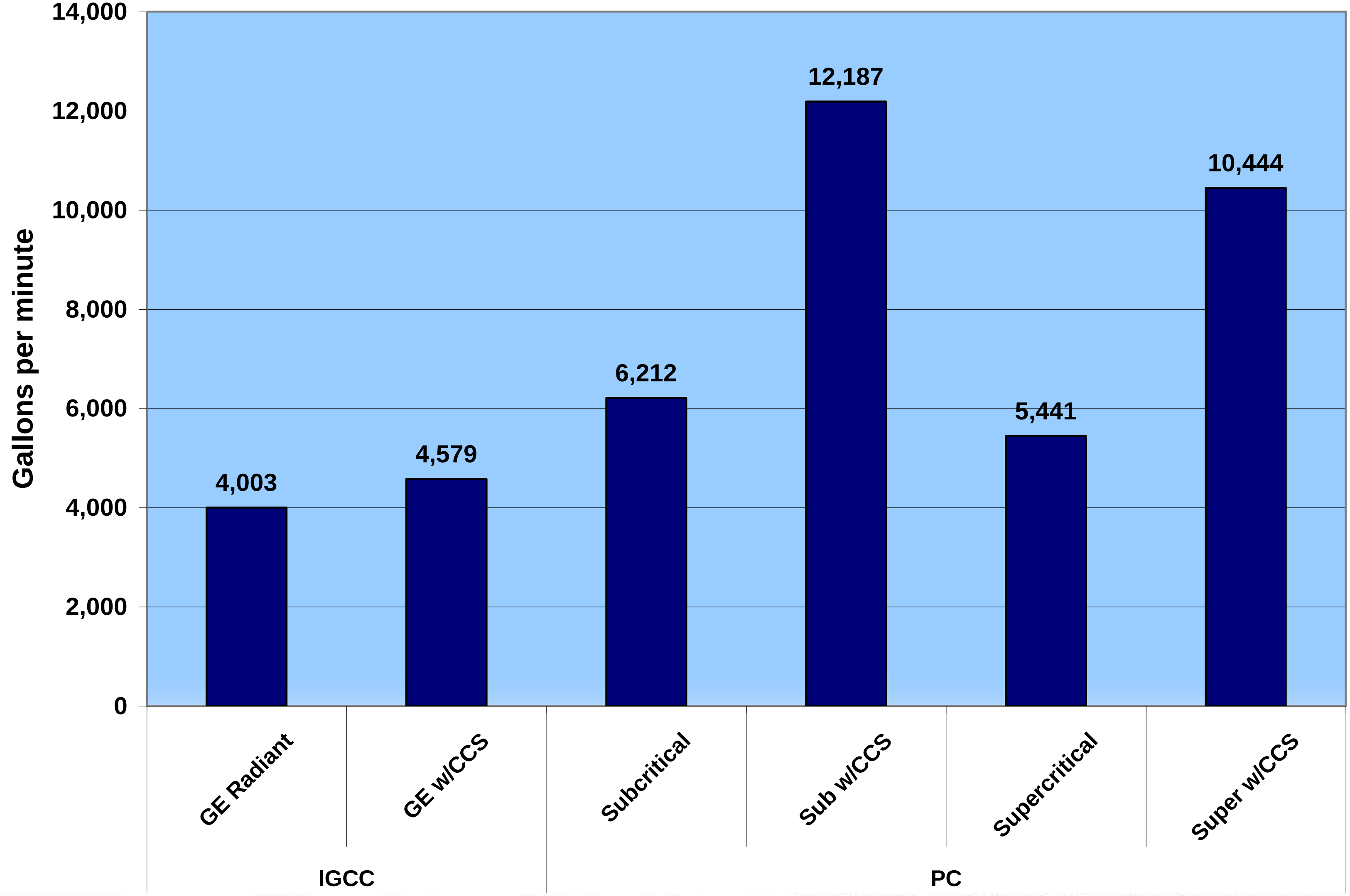
CO_2 Emissions



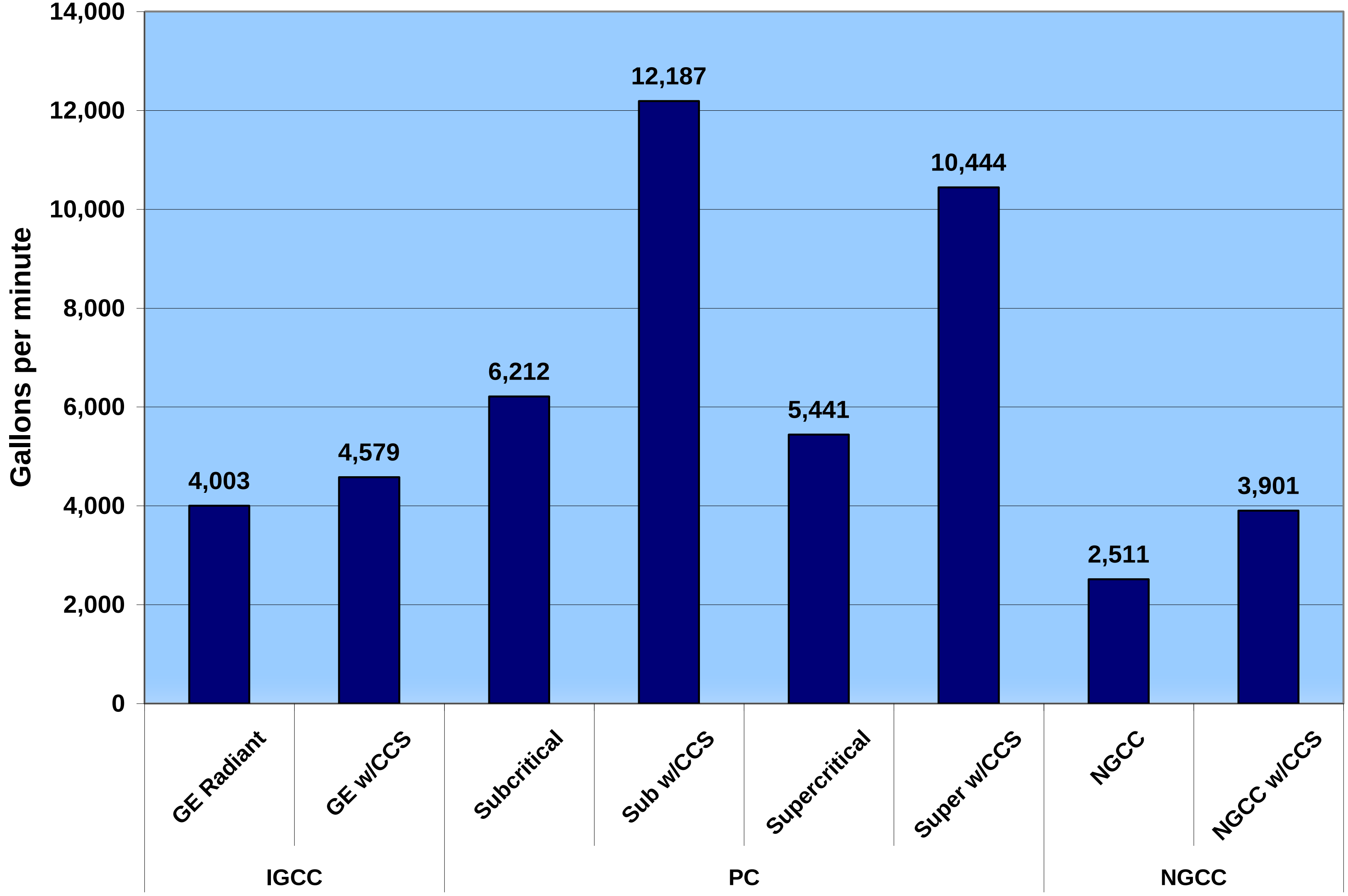
Raw Water Usage Comparison

IGCC, PC and NGCC

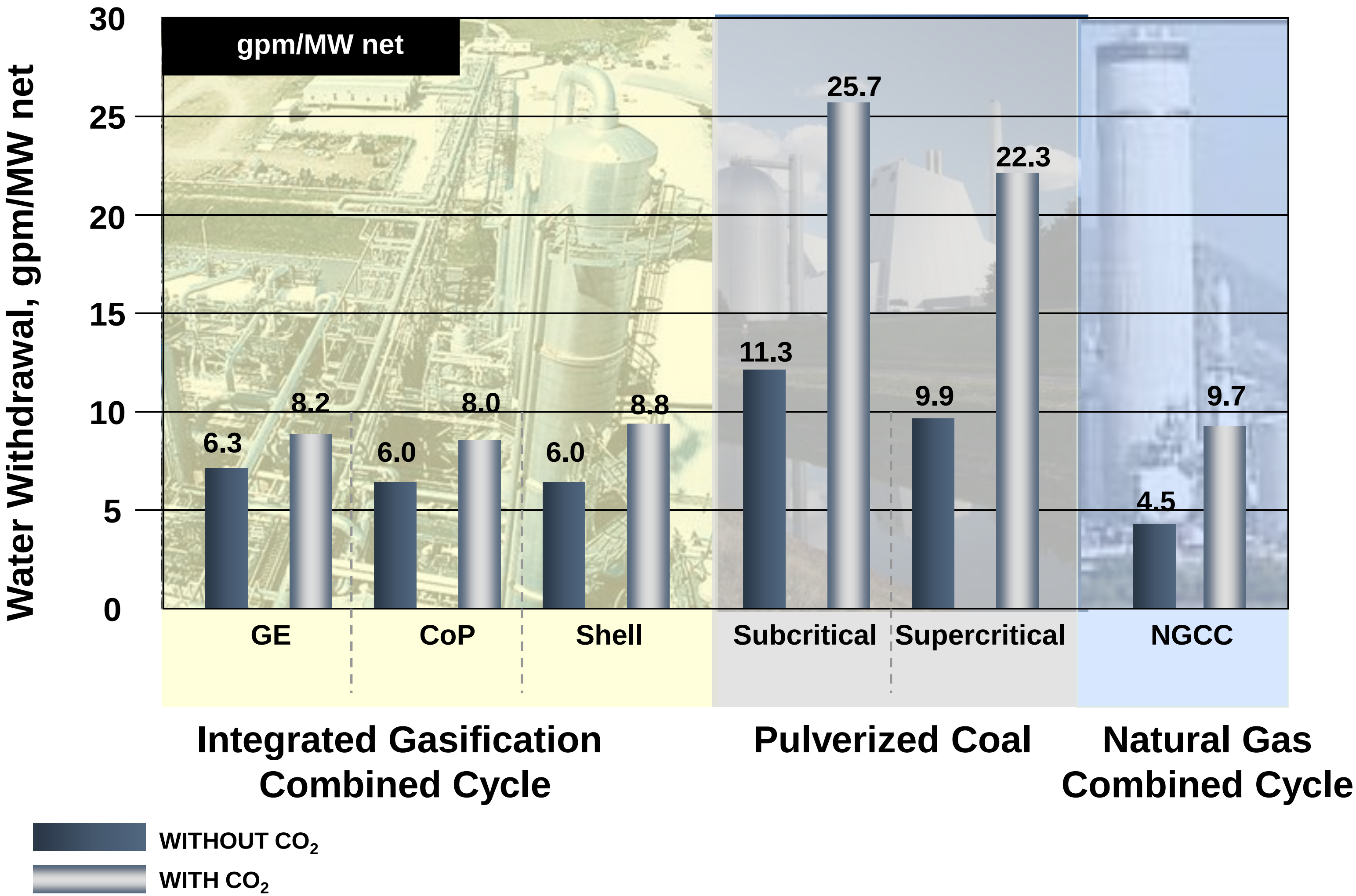
Raw Water Usage Comparison



Raw Water Usage Comparison



Power Plant Water Withdrawal Requirements *with and without CO_2 Capture*



NATIONAL ENERGY TECHNOLOGY LABORATORY

Source: Coal and Performance Baseline for Fossil Energy Power Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity; NETL, May 2007

Economic Results for All Cases

Economic Assumptions

Startup	**2010**
Plant Life (Years)	**20**
Capital Charge Factor	
High Risk	
(All IGCC, PC/NGCC with CO_2 capture)	**17.5**
Low Risk	
(PC/NGCC without CO_2 capture)	**16.4**
Dollars (Constant)	**2007**
Coal ($/MM Btu)	**1.80**
Natural Gas ($/MM Btu)	**6.75**
Capacity Factor	
IGCC	**80**
PC/NGCC	**85**

IGCC Economic Results

No CO_2 Capture

	GE Energy	E-Gas	Shell
Plant Cost ($/kWe)[1]			
Base Plant	1,323	1,272	1,522
Air Separation Unit	287	264	256
Gas Cleanup	203	197	199
Total Plant Cost ($/kWe)	**1,813**	**1,733**	**1,977**
Capital COE (¢/kWh)	4.53	4.33	4.94
Variable COE (¢/kWh)	3.27	3.19	3.11
Total COE[2] (¢/kWh)	**7.80**	**7.52**	**8.05**

[1]Total Plant Capital Cost (Includes contingencies and engineering fees)

[2]January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost $1.80/10^6$Btu

IGCC Economic Results

	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Plant Cost (\$/kWe)[1]						
Base Plant	1,323	1,566	1,272	1,592	1,522	1,817
Air Separation Unit	287	342	264	329	256	336
Gas Cleanup/CO_2 Capture	203	414	197	441	199	445
CO_2 Compression	-	68	-	69	-	70
Total Plant Cost (\$/kWe)	**1,813**	**2,390**	**1,733**	**2,431**	**1,977**	**2,668**
Capital COE (¢/kWh)	4.53	5.97	4.33	6.07	4.94	6.66
Variable COE (¢/kWh)	3.27	3.93	3.20	4.09	3.11	3.97
CO_2 TS&M COE (¢/kWh)	0.00	0.39	0.00	0.41	0.00	0.41
Total COE[2] (¢/kWh)	**7.80**	**10.29**	**7.53**	**10.57**	**8.05**	**11.04**
Increase in COE (%)	**-**	**32**	**-**	**40**	**-**	**37**
\$/tonne CO_2 Avoided	-	35	-	45	-	46

[1]Total Plant Capital Cost (Includes contingencies and engineering fees)

[2]January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost \$1.80/10^6Btu

PC and NGCC Economic Results

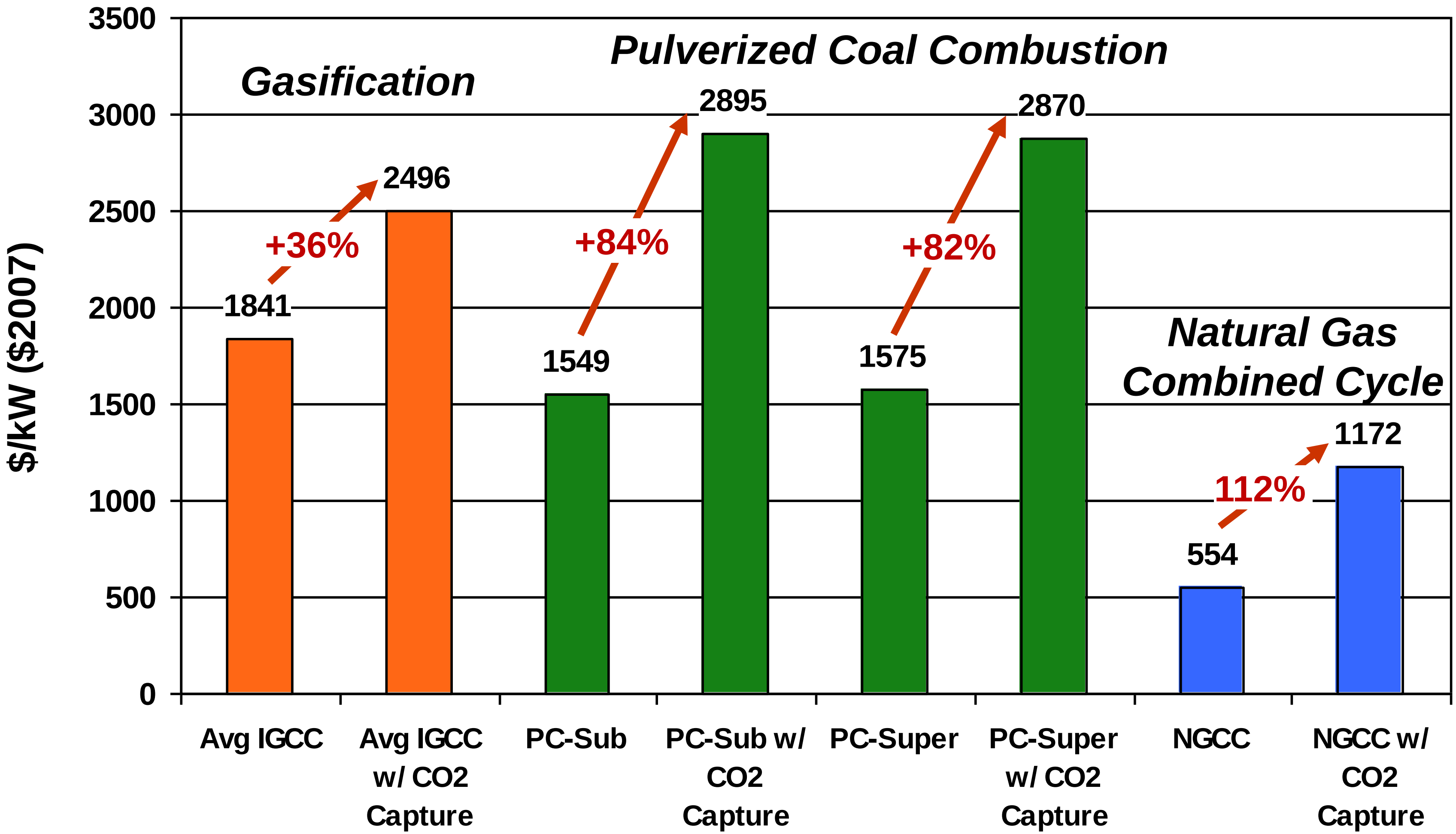
	Subcritical		Supercritical		NGCC	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Plant Cost ($/kWe)[1]						
Base Plant	1,302	1,689	1,345	1,729	554	676
Gas Cleanup (SOx/NOx)	246	323	229	302	-	-
CO_2 Capture	-	792	-	752	-	441
CO_2 Compression	-	89	-	85	-	52
Total Plant Cost ($/kWe)	**1,549**	**2,895**	**1,575**	**2,870**	**554**	**1,172**
Capital COE (¢/kWh)	3.41	6.81	3.47	6.75	1.22	2.75
Variable COE (¢/kWh)	2.99	4.64	2.86	4.34	5.62	6.70
CO_2 TS&M COE (¢/kWh)	0.00	0.43	0.00	0.39	0.00	0.29
Total COE[2] (¢/kWh)	**6.40**	**11.88**	**6.33**	**11.48**	**6.84**	**9.74**
Increase in COE (%)	**-**	**85**	**-**	**81**	**-**	**43**
$/tonne CO_2 Avoided	-	75	-	75	-	91

[1]Total Plant Capital Cost (Includes contingencies and engineering fees)

[2]January 2007 Dollars, 85% Capacity Factor, 16.4% (no capture) 17.5% (capture) Capital Charge Factor, Coal cost $1.80/10^6Btu, Natural Gas cost $6.75/10^6Btu

Capturing CO_2 with Today's Technology is Expensive

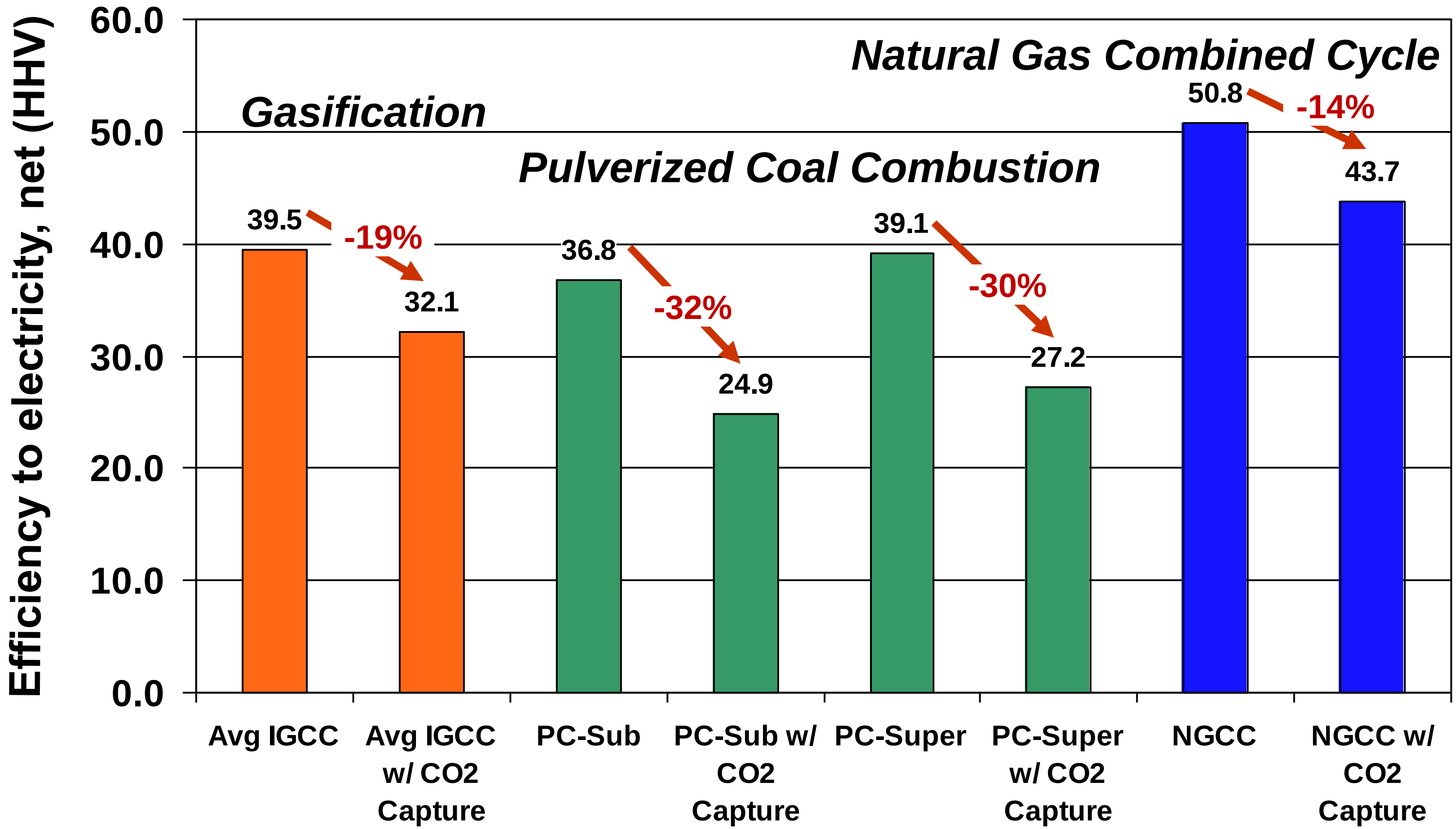
Total Plant Cost Comparison



Total Plant Capital Cost includes contingencies and engineering fees

DOE/NETL Report: "Cost and Performance Baseline for Fossil Energy Plants", May 2007

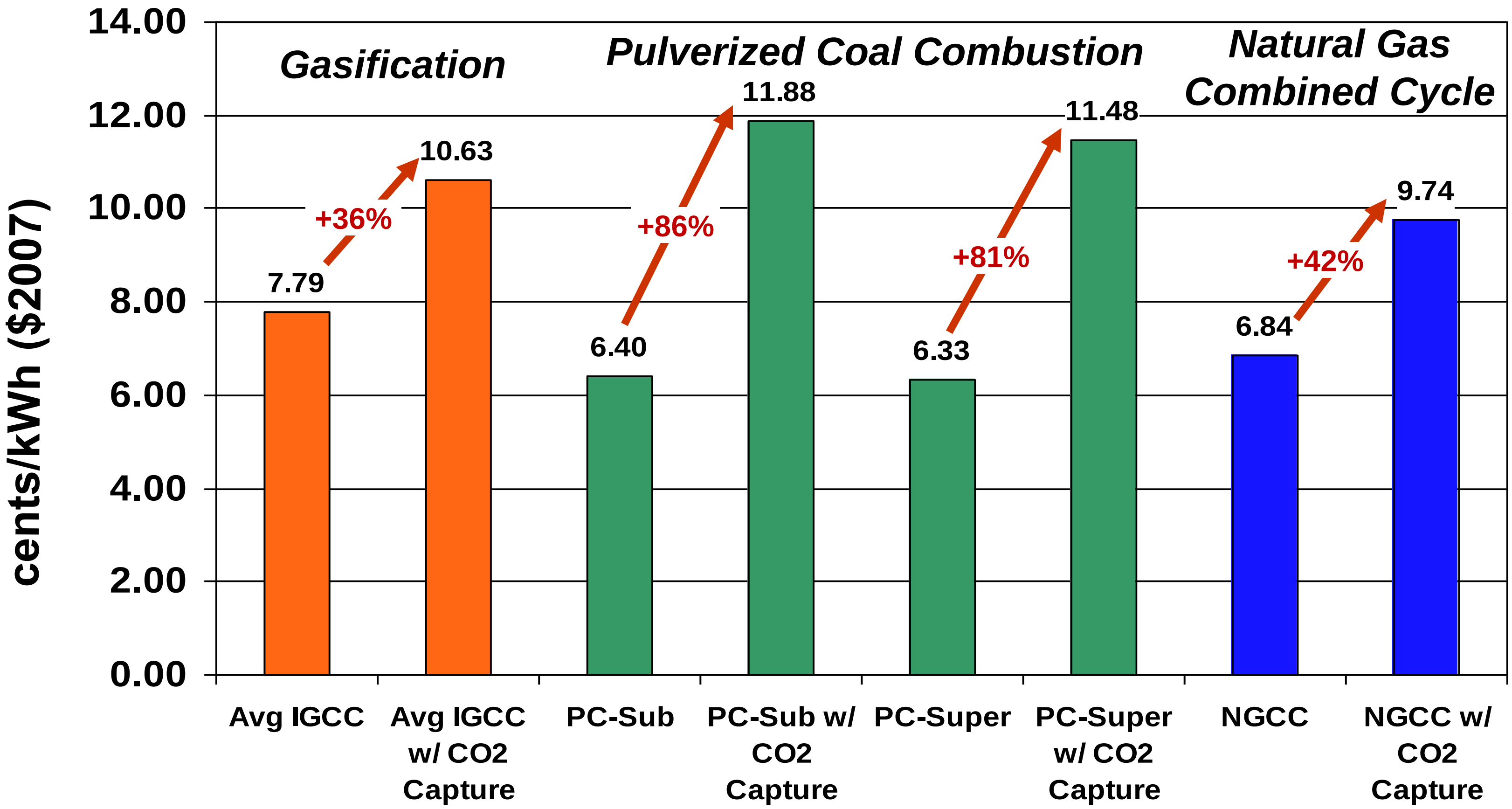
Capturing CO_2 with Today's Technology
Significantly Reduces Plant Efficiency



DOE/NETL Report: "Cost and Performance Baseline for Fossil Energy Plants", May 2007

Capturing CO_2 with Today's Technology is Expensive

Cost of Electricity Comparison



DOE/NETL Report: "Cost and Performance Baseline for Fossil Energy Plants", May 2007

… the Benefits

GASIFICATION

- **Stable, affordable, high-efficiency energy supply with a minimal environmental impact**
- **Feedstock Flexibility/Product Flexibility**
- **Flexible applications for new power generation, as well as for repowering older coal-fired plants**

BIG PICTURE

- **Energy Security -- Maintain coal as a significant component in the US energy mix**
- **A Cleaner Environment (reduced emissions of pollutants)**
  - **The most economical technology for CO_2 capture**
- **Ultra-clean Liquids from Coal -- Early Source of Hydrogen**

Visit NETL Gasification Website

www.netl.doe.gov/technologies/coalpower/gasification/index.html